REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
11/00/79

3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE
EXPECTED FLUORIDE CONTAMINANT LOADING WITHIN EXPANDED NORTH BOUNDARY CONTROL SYSTEM

5. FUNDING NUMBERS

6. AUTHOR(S)
CAMPBELL, D.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
ARMY TOXIC AND HAZARDOUS MATERIALS AGENCY
ABERDEEN PROVING GROUND, MD

8. PERFORMING ORGANIZATION REPORT NUMBER
81266R39

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
GEOTECHNICAL SURVEYS HAVE BEEN RECENTLY COMPLETED IN THE NORTH BOUNDARY VICINITY OF ROCKY MOUNTAIN ARSENAL TO DEFINE THE ARSENAL'S SUBSURFACE HYDROGEOLOGY. WATER TABLE MEASUREMENTS & PERMEABILITY ESTIMATES HAVE BEEN GENERATED TO REFINE FLOW DIRECTION AND QUANTIFY GROUND WATER MOVEMENT OF THE ALLUVIAL AQUIFER AS IT FLOWS ACROSS THE NORTH BOUNDARY. THIS DOCUMENT PRESENTS A COMPILATION OF DATA ASSESSMENTS BASED UPON THE AFOREMENTIONED SURVEY RESULTS ON EXPECTED FLUORIDE CONTAMINANT LOADING WITH THE PROPOSED EXPANDED NORTH BOUNDARY CONTROL SYSTEM. AS A RESULT OF THESE ASSESSMENTS, IT HAS BEEN DETERMINED THAT THERE IS A GOOD POSSIBILITY THAT FLUORIDE LEVELS WITHIN THE EXPANDED TREATMENT SUBSYSTEM WILL BE NATURALLY BELOW THE STATE OF COLORADO LIMIT, THIS MAY NEGATE THE NEED TO ADD A COSTLY FLUORIDE REMOVAL MODULE TO THE PROPOSED GRANULAR CARBON ORGANIC REMOVAL PROCESS.

14. SUBJECT TERMS
TREATMENT, GROUNDWATER, HYDROGEOLOGY, CONTAMINATION, FLUORIDE CONCENTRATION

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
UNCLASSIFIED

18. SECURITY CLASSIFICATION OF THIS PAGE

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT

81266R39

EXPECTED FLUORIDE CONTAMINANT LOADING WITHIN EXPANDED NORTH BOUNDARY CONTROL SYSTEM

Compiled by:

Donald L. Campbell
US Army Toxic and Hazardous Materials Agency
Aberdeen Proving Ground, Maryland 21010

November 1979

EXECUTIVE SUMMARY

Geotechnical surveys have been recently completed in the north boundary vicinity of Rocky Mountain Arsenal (RMA) to define the Arsenal's subsurface hydrogeology. Water table measurements and permeability estimates have been generated to refine flow direction and quantify groundwater movement of the alluvial aquifer as it flows across the north boundary. This document presents a compilation of data assessments based upon the aforementioned survey results on expected fluoride contaminant loading within the proposed expanded north boundary control system.

Groundwater at RMA acts as one continuous hydrogeologically connected unit flowing from south to north. Locally in the north boundary vicinity the alluvial aquifer can best be envisioned as two separate subsurface water units which ultimately make up one alluvial flow crossing the Arsenal's north boundary. The most potentially troublesome groundwater unit moves beneath Basin F in a northeasternly direction toward the north boundary. Contaminants leached from surface waste basins move within this subsurface flow and cross the boundary in the immediate area of the present pilot containment/treatment system. The other groundwater unit flows northwesternly beneath and parallel to the First Creek surface stream. This alluvial pathway is relatively free of contaminants and has a much larger volume than does the contaminated groundwater flow. As both subsurface flows approach the north boundary, water table contours straighten and become parallel to the Arsenal boundary. In this area groundwater flow is directly northward with some contaminants crossing the boundary throughout the alluvial aquifer.

Based upon results of these surveys, a decision has been made by the Army to expand the 1500 foot north boundary pilot containment/treatment system. Applicable water quality guidelines (particularly the 0.2 ppb State of Colorado limit for DBCP) dictate that the extension must be across the entire northward flowing alluvial aquifer. Thus, current plans call for the present pilot containment system to be expanded approximately 3500 feet eastward and 700 feet westward.

Interception of the entire alluvial aquifer will result in compositing both the contaminated and relatively noncontaminated groundwater flow units described above. For design purposes, assessments have been completed to identify expected contaminant loadings within the composite stream to be handled by the expanded control system. In July 1979 D'Appolonia Consulting Engineers provided a conceptual design of the extension of the pilot containment subsystem to the east and west. Fluoride was among four pollutants examined to predict total quantities of contaminants to be intercepted. A second assessment, performed by US Army Toxic and Hazardous Materials Agency (USATHAMA) utilized the same geotechnical survey data base to predict contaminant loadings to the expanded pilot treatment subsystem.

As a result of these assessments, it has been determined that there is a good possibility that fluoride levels within the expanded treatment subsystem will be naturally below the State of Colorado limit. This may negate the need to add a costly fluoride removal module to the proposed granular carbon organic removal process. The results of these assessments are summarized below:

	Assessment A: D'Appolonia Consulting Engineers	Assessment B: US Army Toxic and Hazardous Materials Agency
Alluvial Flow Rate (gpd)	638393	882200
Total Fluoride Migrating off N. Boundary of RMA (kg/day)	6.6	7.8
Expected Manifolded Fluoride Concentration (mg/ℓ)	2.7	2.3
State of Colorado Standard (mg/ℓ)	2.4	2.4

Variations noted in the estimates are due to differences in the choice of aquifer hydrodynamic parameters. Permeability estimates for the most permeable aquifer material range from 400 to 600 feet per day for the D'Appolonia and USATHAMA assessments, respectively. Equal variation is noted in saturated thickness estimates. These differences are within an acceptable range, however. Geohydrologic definition is not an exact science and is commonly assumed adequate if an 80 percent accuracy is achieved. It is emphasized that both assessments are considered valid within the limits of the accuracy of the data. Refinement of the flow and fluoride concentration expectations will not be possible until actual expanded system operation is accomplished.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

1.0 INTRODUCTION

The Rocky Mountain Arsenal (RMA) is located approximately 10 miles northeast of the central business district of Denver, Colorado and immediately north of the Stapleton International Airport (Figure 1). RMA was established in 1942 and historically has either produced toxic chemicals and chemical filled munitions, or demilitarized these same items. In 1946, a large portion of the manufacturing facilities was leased to private industry for the production of herbicides and insecticides. Chemical wastes generated collectively by these operations have been discharged into several waste storage basins located on the Arsenal grounds.

The first reported indication of off-post contamination occurred in the summer of 1951, when some crop damage was reported on an irrigated field northwest of the RMA (Kolmer & Anderson, 1977). In 1954, several farmers north of the arsenal complained of damage to crops irrigated with water pumped from the alluvial aquifer. Due to these complaints and subsequent damage claims, the Department of the Army initiated several studies. These studies resulted in the construction of a new disposal basin with a low permeability liner (Reservoir "F", see Figure 1). Since 1957, all chemical wastes have been pumped into this reservoir.

In May 1974, diisopropyl methylphosphonate (DIMP) and dicyclopentadiene (DCPD) were detected in waters discharging from a bog located along the north boundary of the RMA. DIMP was also detected in water supply wells for the city of Brighton in December of 1974. DIMP is a persistent compound produced in small quantities during the manufacture of GB, a chemical warfare agent. DCPD is a chemical used in the production of insecticides. The off-post detection of DIMP and DCPD prompted the Colorado Department of Health to issue three Cease Orders on April 7,

1975, that required an immediate stop to surface and subsurface discharge of DIMP and DCPD, development of a plan to preclude future discharge of the contaminents, and development of a monitoring program to verify compliance with these orders.

In the summer of 1976 analysis of groundwater from the north boundary also revealed the presence of inorganic fluorides and three organic sulfur compounds (p-chlorophenyl methyl sulfide, p-chlorophenyl methyl sulfoxide, and p-chlorophenyl methyl sulfone). In 1978, dibromochloropropane (DBCP or Nemagon) was discovered in the groundwater in the vicinity of the north boundary of the Arsenal. Although these compounds were not cited in the Cease and Desist Orders, they are included in the list of compounds requiring treatment.

From 1975 to 1977, several investigators were involved in hydrologic investigations and the design of a containment and treatment system for a portion of the northern boundary of the RMA. These studies and reviews were conducted by Konikow (1975), Reynolds (1975), Miller (1977), Mitchell (1976), Kolmer and Anderson (1977a and b), Thomas, et al., (1977), and Robson (1976). The studies resulted in the installation of the present pilot containment system along a portion of the northern RMA boundary (Figure 1).

The selected system design for containment and treatment of contaminated groundwater relies on the use of an impermeable barrier (bentonite slurry wall) to impede the natural subsurface flow of ground water across the boundary. Groundwater flowing toward the barrier is removed from the upgradient side of the barrier by dewatering wells and treated for the removal of organic contaminants. The treated water is then injected into the aquifer on the downgradient side of the slurry wall in a line of recharge wells. A schematic representation of the containment system is provided in Figure 2.

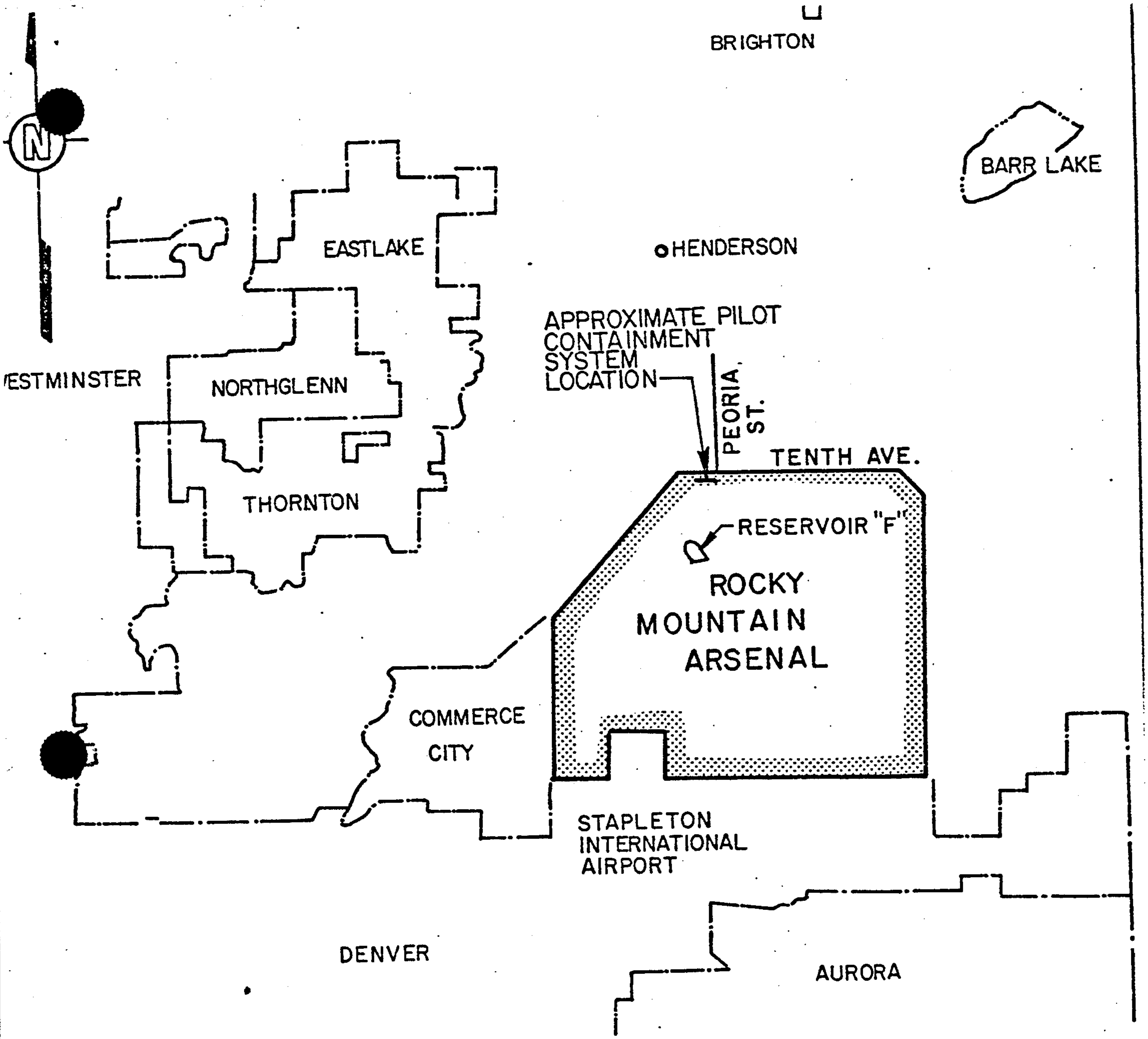
Since installation of the pilot containment/treatment system, additional geohydrologic data has been collected in the north boundary vicinity. This information has been used to:

- Provide a detailed definition of the geology and groundwater in the alluvium between Basin F and the north boundary (Zebell, 1979).
- Provide a description of the locations, movements, and concentrations of various pollutants in the alluvial aquifer (Thompson, 1979).
- Provide an evaluation of the north boundary pilot system after 1 year of operation (D'Appolonia Consulting Engineers, 1979).
- Provide a conceptual design of the extension of the pilot containment system to the east and west (D'Appolonia Consulting Engineers, 1979).

Based on the success of the pilot system, a decision has been made by the Department of the Army to extend the present pilot containment treatment system. The north boundary containment system expansion concept will be designed to recover water flowing in the alluvial aquifer across the north boundary of the RMA with a minimum of changes in the presystem head distribution. Predictions indicate that an average of 450 to 650 gallons per minute (gpm) of groundwater crosses the north boundary under present conditions. The requirement to treat all groundwater containing DBCP concentrations above the detection limit of 0.2 ppb dictates that this entire northward flowing aquifer must be controlled and intercepted. A 3500 foot eastward and 700 foot westward expansion to the pilot system is currently planned.

Particular attention has been given to the prediction of DIMP, DBCP, and fluoride contaminant loadings to the treatment system once the groundwater is manifolded after dewatering. This analysis is limited to the issue of fluoride. Independent assessments have been recently completed by private contractor and Government personnel. The following sections delineate results of these efforts.

- o Section 2: Site Hydrology.
- o Section 3: Assessment A performed by D'Appolonia Consulting Engineering
- o Section 4: Assessment B performed by US Army Toxic and Hazardous Materials Agency.
- o Section 5: Conclusions



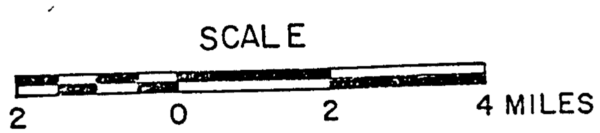


FIGURE I

VICINITY MAP

NORTH BOUNDARY CONTAINMENT SYSTEM
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PREPARED FOR

BATTELLE COLUMBUS LABORATORIES
COLUMBUS, OHIO

D'APPOLONIA

REFERENCE:
KOLMER AND ANDERSON, 1977B.

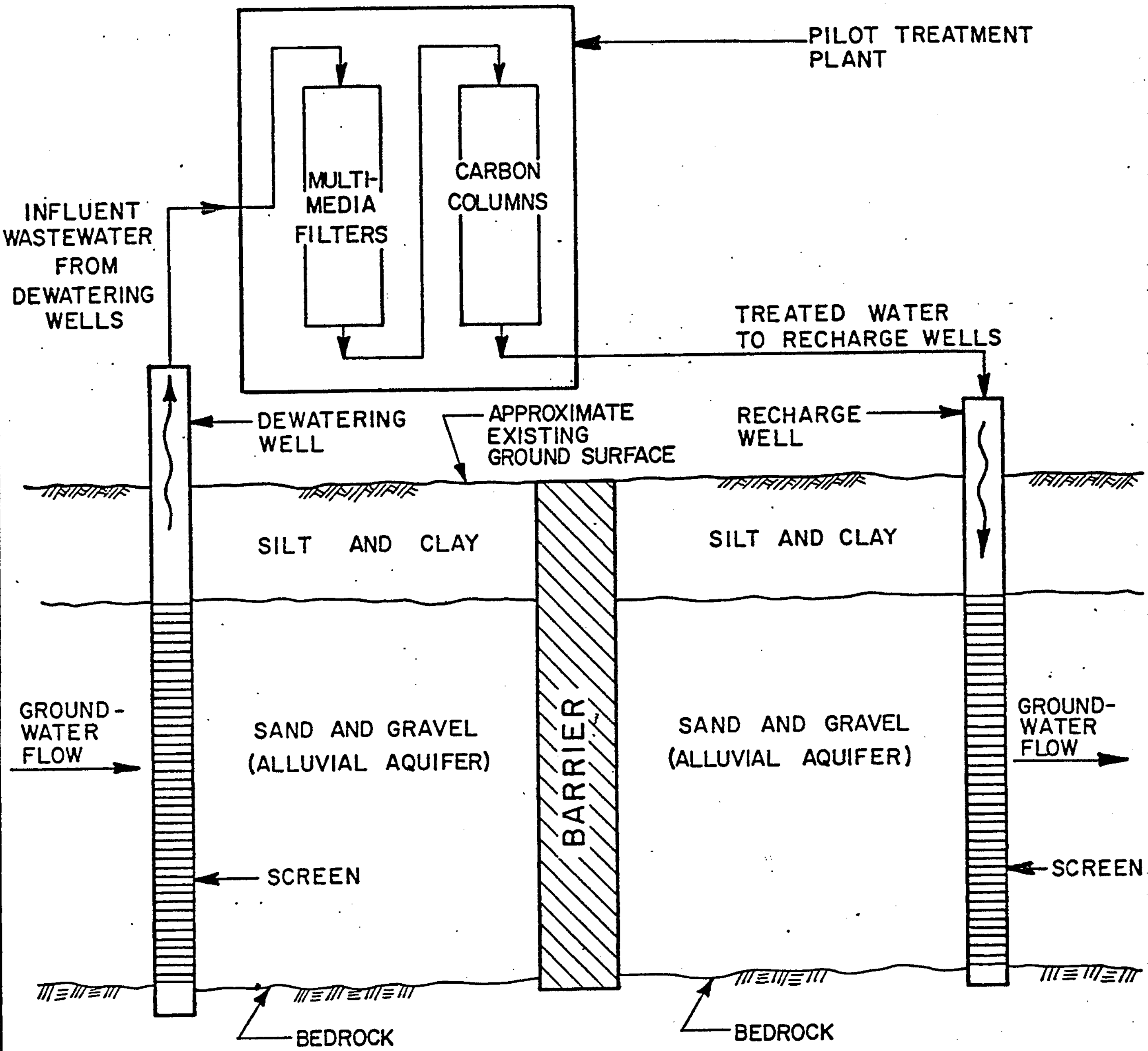


FIGURE 2

SCHEMATIC DIAGRAM OF CONTAINMENT SYSTEM

NORTH BOUNDARY CONTAINMENT SYSTEM
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PREPARED FOR

BATTELLE COLUMBUS LABORATORIES
COLUMBUS, OHIO

D'APPOLONIA

BIBLIOGRAPHY

D'Appolonia, 1979, Report: Conceptual Design of the North Boundary Containment System, Rocky Mountain Arsenal, Denver, Colorado, Project No. RM79-480.

D'Appolonia, 1979, Report: Evaluation of North Boundary Pilot Containment System, Rocky Mountain Arsenal, Denver, Colorado, Project No. RM79-389.

Kolmer, J. R., and G. A. Anderson, 1977a, Installation Restoration of Rocky Mountain Arsenal, Part 1 - Pilot Containment Operations, Draft Environmental Impact Statement, Office of the Project Manager for Chemical Demilitarization and Installation Restoration, U.S. Army.

Kolmer, J. R. and G. A. Anderson, 1977b, Installation Restoration of Rocky Mountain Arsenal, Part 1 - Pilot Containment Operations, Final Environmental Impact Statement, Office of the Project Manager for Chemical Demilitarization and Installation Restoration, U.S. Army.

Konikow, L. F., 1975, Hydrogeologic Maps of the Alluvial Aquifer in and Adjacent to the Rocky Mountain Arsenal, U.S. Geol. Survey open-file report 74-342.

Miller, S. P., 1977, Visit to Rocky Mountain Arsenal 24-25 January, 1977, Memorandum for Record, U.S. Army Corps of Engineers, Waterways Experiment Station.

Mitchell, G. B., 1976, "Interim Containment System, Rocky Mountain Arsenal, Memorandum for Record, Waterways Experiment Station," U.S. Army Corps of Engineers.

Reynolds, J. W., 1975, "Rocky Mountain Arsenal Off-Post Containment Control Plan," U. S. Army Armament Command, Rocky Mountain Arsenal.

Robson, S. G., 1976, "Digital Model Study of Ground Water Contamination by DIISOPROPYLMETHYLPHOSPHONATE (DIMP) Rocky Mountain Arsenal near Denver, Colorado, "Final Report to U. S. Dept. of the Army, Rocky Mountain Arsenal, U.S. Geol. Survey Administrative Report.

Thomas, T. J., S. Smith, and H. Eagon, 1977, "Study of Alternatives for Ground Water Pollution Control at the North Boundary of Rocky Mountain Arsenal," Report to Project Manager for Chemical Demilitarization and Installation Restoration, Department of the Army, Battelle Columbus Laboratories and Moody and Associates.

Thompson, Douglas W. and Law, Paul K., 1979, Basin F to the North Boundary, Volume II: Groundwater Definition, Rocky Mountain Arsenal, Denver, Colorado, U.S. Army Corps of Engineers, Waterways Experiment Station.

Zebell, Robert A., 1979, Basin F to the North Boundary, Volume I: Geotechnical Definition, Rocky Mountain Arsenal, Denver, Colorado, U.S. Army Corps of Engineers, Waterways Experiment Station.

THIS PAGE INTENTIONAL LEFT BLANK

2.0 SITE HYDROGEOLOGY

The hydrogeologic system of concern along the north boundary of the RMA consists of an unconsolidated alluvial sand and gravel aquifer that overlies a much lower permeability shale and claystone bedrock. Subsurface flow of contaminated groundwater to the north takes place within this alluvial aquifer and results in a discharge across the north boundary of the Arsenal.

2.1 BEDROCK COMPOSITION AND TOPOGRAPHY

The alluvial aquifer is underlain by predominantly shale and claystone bedrock of the Denver Formation. Previous studies of the groundwater contamination have assumed that the major portion of flow takes place within the alluvium due to the extreme permeability contrast between the bedrock and unconsolidated alluvial units. A number of deep borings show that the bedrock is composed primarily of shale and claystone with occasional silt lenses. Some poorly cemented sandstones have also been found, including one continuous unit, about 4 feet thick, that can be traced through several borings over a distance of greater than 2,000 feet. Other sandstones up to 12 feet thick appear to be lenticular.

A weathered zone is found in the shales extending to 25 to 35 feet below ground surface in the lower lying areas and up to 50 feet below ground surface in the higher areas. This weathered zone generally extends from 5 to 15 feet below the bedrock alluvium contact. At the eastern end of the existing slurry wall, the weathered zone extends approximately 7 feet below the bottom of the wall.

The sandstones within the bedrock and the weathered material close to the bedrock surface may locally be permeable. However, the assumption that the bedrock is impermeable relative to the alluvial aquifer is believed to be valid. Evaluation of the possible minor flows within the bedrock is not included in the scope of this study, nor does it currently appear warranted.

A large data base exists to evaluate the material properties (both of the bedrock and unconsolidated alluvial deposits) within and to some degree in the near vicinity of the Arsenal grounds. The location of the available boreholes and wells is provided in Figure 3. The same quality and type of information is not available for some of the boreholes and wells shown in Figure 3. Consequently any one of the representations developed from this data base does not typically include information from all the boreholes or wells present in Figure 3. Relative to defining the top of bedrock the majority of the locations identified in Figure 3 provided usable information that D'Appolonia was able to develop into an accurate top of bedrock contour map (Figure 4).

2.2 AQUIFER PROPERTIES

For the majority of the existing boring logs, the materials characteristics of the unconsolidateddeposits were indicated only by a Unified Soil Classification System (USCS) group symbol. The following USCS groups were typically considered to be aquifers:

GW - well graded gravels, gravel-sand mixtures, little or no fines.

GP - poorly graded gravels, gravel-sand mixtures, little or no fines.

GM - Silty gravels, poorly graded gravel-sand-silt mixtures.

GC - clayey gravels, poorly graded gravel-sand-clay mixtures.

SW - well graded sands, gravelly sands, little or no fines.

SP - poorly graded sands, gravelly sands, little or no fines

SM - silty sands, poorly graded sand-silt mixtures

SC - clayey sands, poorly graded sand-clay mixtures

Various combinations of these groups such as SPGP and SPSM were also considered.

Permeability values for the sand, and sand and gravel units were obtained from aquifer tests in 1976 (Mitchell, 1976) and 1978 (Vispi, 1978). D'Appolonia (1979) evaluated these test results and estimated representative permeabilities for the sand, and sand and gravel units of about 3,000 gpd/ft^2 (400 ft/day) and 5,000 gpd/ft^2 (668 ft/day), respectively. An order of magnitude reduction in permeability exists for units that contain appreciable silt. Any unit containing clay has a negligible permeability compared with the clean sands, and sand and gravels.

The potential variance or error present in the USCS designations on the Arsenal's data is important to note when evaluating boring logs that have been accumulated over a period as long as 20 years. The exact distinction of clayey or silty soils in the USCS can frequently only be made via laboratory tests (liquid limit and plastic limit). In the field, these parameters can be difficult to accurately quantify unless the observer(s) has substantial experience. Therefore, the possibility exists that a soil classified as silty in one boring, for example, may have been described as clayey in another boring by a different inspector. In addition, relatively small amounts of clay or silt may significantly affect permeability values. For these reasons, permeability distributions from the boring logs alone are difficult to interpret in exact terms.

2.3 ALLUVIAL AQUIFER THICKNESS AND DISTRIBUTION

Figure 5 is a plot of alluvial aquifer thickness as indicated by the existing boring logs. The aquifer is defined as all sand and gravel, gravel, and sand units that are either unconfined or confined below an impermeable layer. In both cases, the aquifer thickness is the thickness of permeable materials above and below the water table. Permeable deposits lying above a confining layer are included only if partly or wholly saturated, the thickness counted being the thickness of the

entire permeable zone above and below the saturated zone. To evaluate the saturated thickness, the difference between the potentiometric and bedrock surface was used.

The thickness of the aquifer varies from zero on bedrock highs to a recorded maximum of 41 feet about 1 mile south of the containment system. As shown in Figure 5, thicknesses are generally greater in the southern and central portions of the area of interest. The contoured data illustrates the presence of two sediment troughs that correspond approximately with the bedrock valleys described above. In detail, many locations show a significant variation in thickness over a short horizontal distance. This variation is probably real resulting from the lenticular nature of coarser grained channel fill deposits within the aquifer. In some cases, however, the variation may be due in part to differing interpretations of the material properties of the same deposits during logging. The use of smoothed contours highlights the major trends in the aquifer rather than minor channeling effects.

Working cross-sections were prepared at various locations across the aquifer normal to the direction of groundwater flow to assess aquifer continuity. These sections suggest that the aquifer is relatively continuous. While the thickness does vary locally there are not significant continuous impermeable barriers between the deeper permeable channel fill deposits that could have a significant effect on flow direction and distribution.

2.4 PERMEABILITY DISTRIBUTION

As noted in Section 2.2, silty units have a significantly lower permeability than the clean sands or sands and gravels. Lithologic maps were prepared for working purposes to show the predominant character of the alluvial aquifer. These maps show a tendency for a higher proportion of silty units towards the east and within the deeper aquifer channel fill deposits. In all cases, when there is a high proportion of silty units, however, adjacent borings show a high proportion of sand or sand and gravel. This observation suggests that there is a

sufficient proportion of sand or sand and gravel throughout the entire aquifer. This result indicates that the aquifer can reasonably be modeled on a relatively macro scale to successfully predict the total flux across the Arsenal's northern boundary. Locally, a concentration of flow within restricted channels of higher permeability would be expected to be present. It is not, however, practical to model these channels given the existing data (despite the large number of borings) and the complex micro flow systems.

2.5 POTENTIOMETRIC SURFACE

The average spring prepilot plant potentiometric surface for the spring 1978 is provided in Figure 6a. The potentiometric gradient is generally toward the north with an average gradient of 0.006 ft./ft. (Kolmer and Anderson, 1977). The observed gradient in the bedrock valley between the north boundary and Reservoir "F" is much lower. This observation suggests that the permeability within this zone is much higher than the material along the north boundary where the gradient is steeper.

Alluvium water levels from May to June 1979 (Figure 6b) gathered by Zabell (1979) demonstrate similar flow characteristics. Gradients in the range of 0.006 to 0.008 ft/ft. along the north boundary are evident. Comparison of the data reveal significant similarities suggesting the alluvial groundwater system is presently at or near steady state conditions.

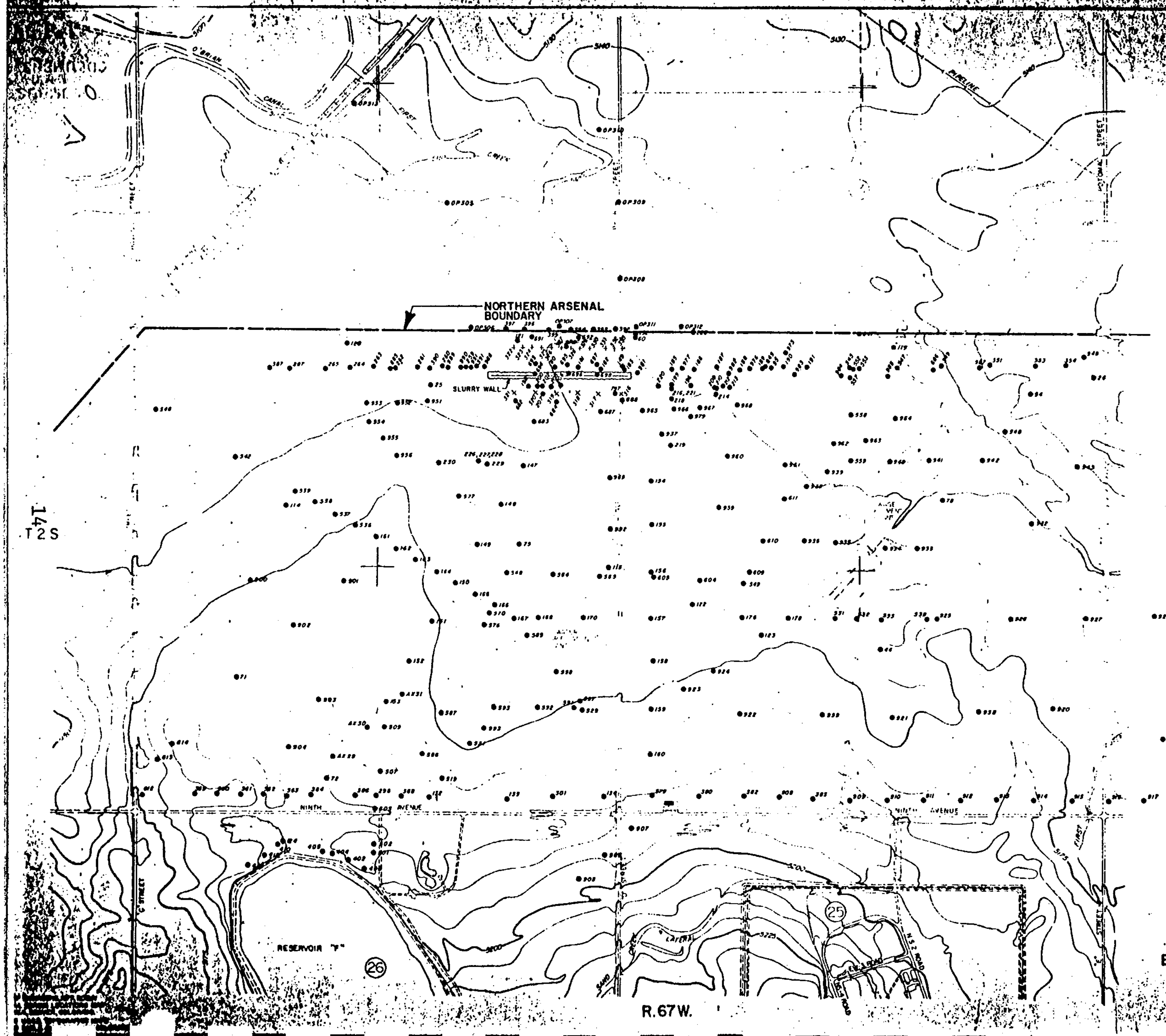


FIGURE 3

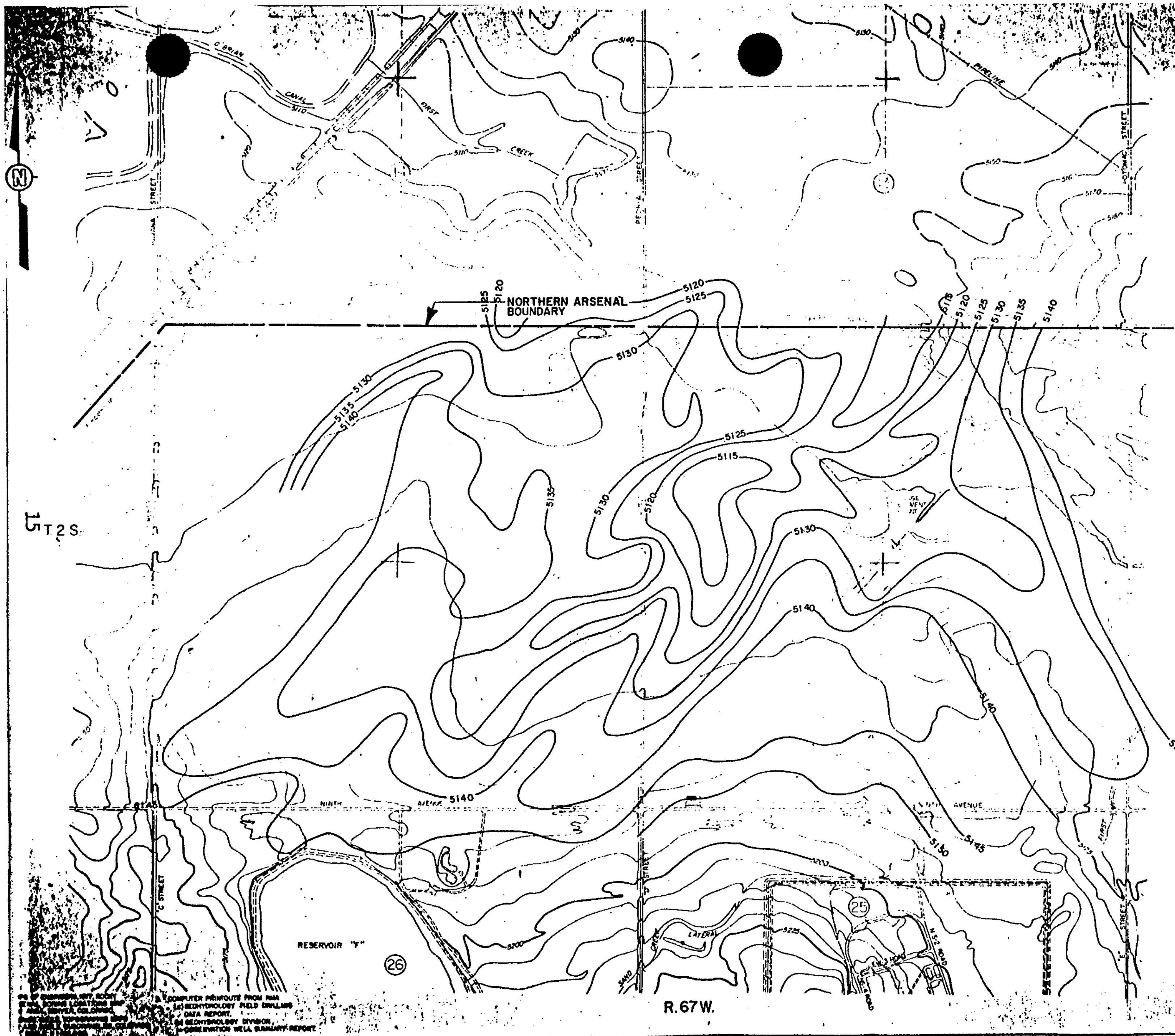
PLAN AND LOCATION OF BOREHOLES AND WELLS

NORTH BOUNDARY CONTAINMENT SYSTEM
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PREPARED FOR

BATTELLE COLUMBUS LABORATORI
COLUMBUS, OHIO

D'APPOLONIA



LEGEND

—5130— BEDROCK ELEVATION CONTOURS (DATUM MEAN SEA LEVEL)

SCALE

500 0 500 1000 FEET

FIGURE 4

TOP OF BEDROCK CONTOUR MA

NORTH BOUNDARY CONTAINMENT SYSTEM
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PREPARED FOR

BATTELLE COLUMBUS LABORATOR
COLUMBUS, OHIO

D'APPOLONI

LEGEND

—10— ALLUVIAL AQUIFER THICKNESS CONTOURS

BOUNDARY BETWEEN UNITS (APPROXIMATE)

AQUIFER BOUNDARIES (APPROXIMATE)

- AQUIFER ABSENT
- AQUIFER CONSISTS PRIMARIL' OF SILTY SANDS
- AQUIFER CONSISTS OF SANDS SANDS AND GRAVELS
- AQUIFER CONSISTS OF SAND / SANDS AND GRAVELS WITH SOME

NOTE: AQUIFER THICKNESS IMPLIES TOTAL THICKNESS OF PRODUCTIVE UNITS WHETHER OR NOT THEY ARE SATURATED

SCALE

500 0 500 1000 F

FIGURE 5

ALLUVIAL AQUIFER THICKNESS MAP

NORTH BOUNDARY CONTAINMENT SYSTE
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PREPARED FOR

BATTELLE COLUMBUS LABORATO
COLUMBUS, OHIO

D'APPOLONIA

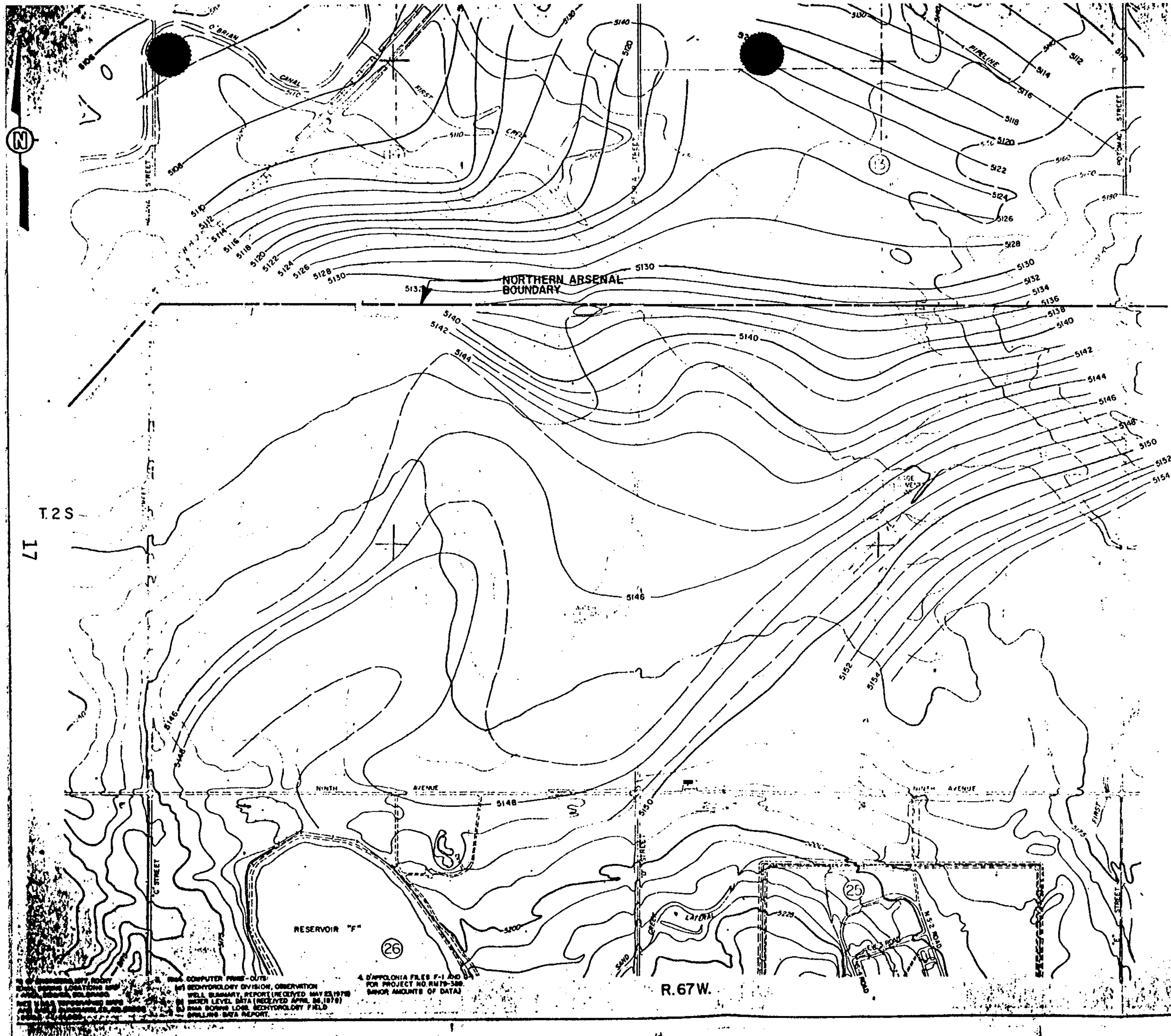


FIGURE 6a

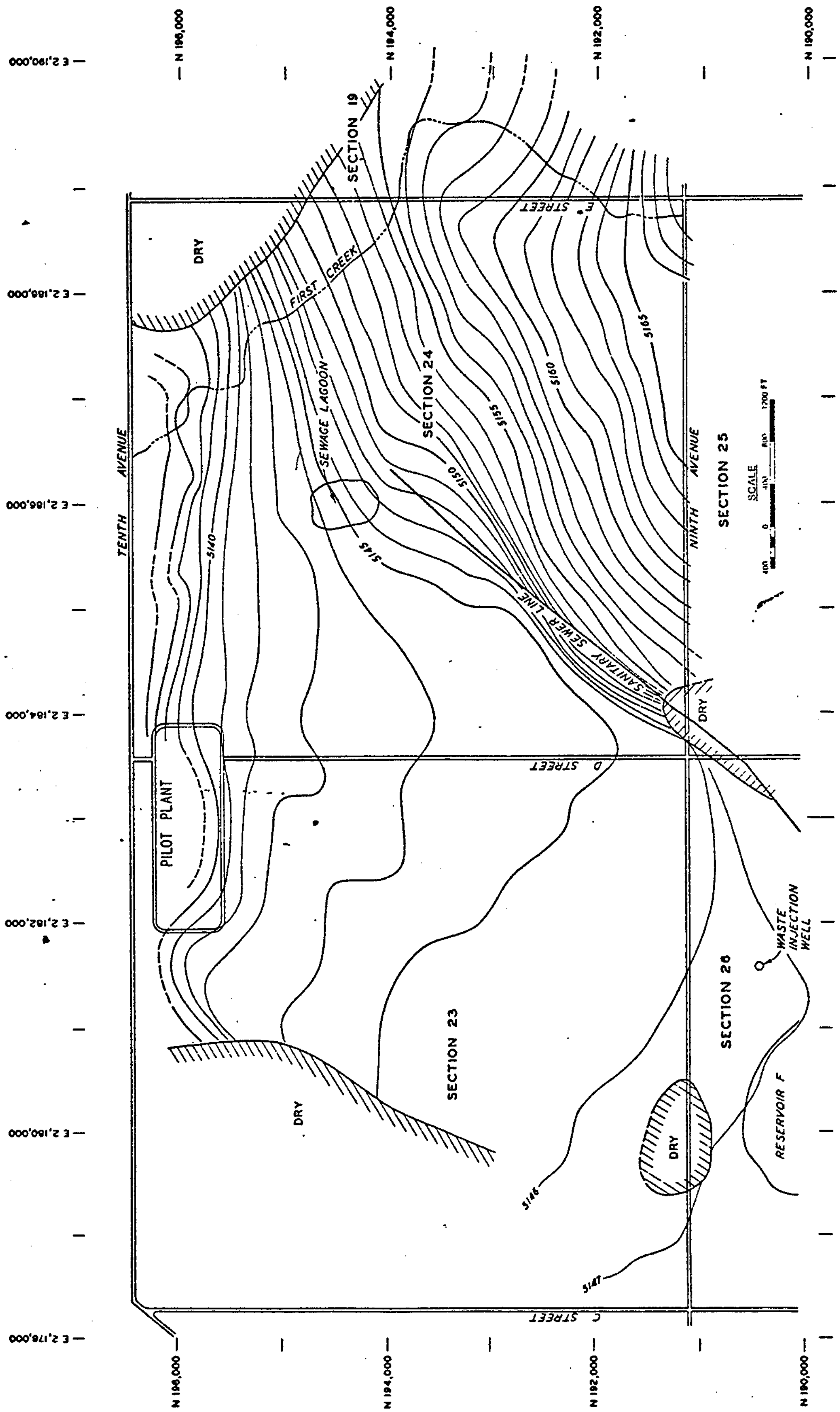
PRESYSTEM SPRING 1978
POTENTIOMETRIC SURFACE MA

NORTH BOUNDARY CONTAINMENT SYSTEM
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PREPARED FOR

BATTELLE COLUMBUS LABORATOR
COLUMBUS, OHIO

D'APPOLONI



Alluvium Water Levels (May–June 1979)

Figure 6b

BIBLIOGRAPHY

D'Appolonia, 1979, Report: Evaluation of North Boundary Pilot Containment System, Rocky Mountain Arsenal, Denver, Colorado, Project No. RM79-389.

Kolmer, J. R., and G. A. Anderson, 1977a, Installation Restoration of Rocky Mountain Arsenal, Part 1 - Pilot Containment Operations, Draft Environmental Impact Statement, Office of the Project Manager for Chemical Demilitarization and Installation Restoration, US. Army.

Kolmer, J. R. and G. A. Anderson, 1977b, Installation Restoration of Rocky Mountain Arsenal, Part 1 - Pilot Containment Operations, Final Environmental Impact Statement, Office of the Project Manager for Chemical Demilitarization and Installation Restoration, U.S. Army.

Mitchell, G. B., 1976, "Interim Containment System, Rocky Mountain Arsenal, Memorandum for Record, Waterways Experiment Station," U.S. Army Corps of Engineers.

Vispi, Mark A., 1978, Report of Finding, Rocky Mountain Arsenal Pumping Test, U.S. Army Corps of Engineers, Waterways Experiment Station.

Zebell, Robert A., 1979, Basin F to the North Boundary, Volume I: Geotechnical Definition, Rocky Mountain Arsenal, Denver, Colorado, U.S. Army rps of Engineers, Waterways Experiment Station.

THIS PAGE INTENTIONALLY LEFT BLANK

3.0 ASSESSMENT A: D'Appolonia Consulting Engineers

To develop an optimum design for the dewatering and recharge subsystems of the north boundary containment system, a conceptual hydrogeologic model was formulated into a finite element mathematical model. The objective of this modeling effort was to evaluate natural subsurface outflow across the RMA's north boundary and to develop performance predictions for the designed system. The combination of a variable potentiometric gradient, contrasts in aquifer permeability and the irregular boundary conditions suggest that the use of a mathematical flow model is desirable to reflect the detailed nature of the available data.

3.1 MODEL DESCRIPTION

The computer program used in this study is a two-dimensional finite element code which simulates the performance of an aquifer on a regional basis. The basic governing equations of the flow regime are well established (Bear, 1972; Pinder and Frind, 1972), and described later in this section. To model the performance of the north boundary alluvial aquifer, the region was divided into a system of grids which are called elements. When hydrodynamic parameters and stresses are provided (such as transmissivity, storage coefficients, pumping and recharge rates), the program calculates time-variable or steady state potentiometric surfaces and consequently the flow vectors of the region. A full description of the methodology used, assumptions made, and accuracy in the program is contained in Appendix A. A summary of this information follows.

Governing Equations

The combined equation of motion and continuity for flow in a two-dimensional horizontal plane can be written:

$$\frac{\partial}{\partial x} T_{xx} \frac{\partial \phi}{\partial x} + \frac{\partial}{\partial y} T_{yy} \frac{\partial \phi}{\partial y} - P = S \frac{\partial \phi}{\partial t} \qquad (1)$$

where:

T_{xx} = principal hydraulic transmissivity along x-direction $[L^2/t]$.

T_{yy} = principal hydraulic transmissivity along y-direction $[L^2/t]$.

ϕ = potentiometric surface [L].

P = the strength of a sink or source $[L^3/L^2t]$.

S = storage coefficient [dimensionless].

x,y = Cartesian coordinates [L].

t = time [t].

$\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial t}$ = partial derivatives with respect to x, y, and t, respectively.

The transmissivity of an aquifer under artesian conditions is the product of the hydraulic conductivity (permeability) and the thickness of that aquifer. Thus,

$$T_{xx} = b\,K_{xx};\quad T_{yy} = b\,K_{yy} \qquad (2)$$

where:

b = thickness of aquifer [L].

K_{xx} = principal hydraulic conductivity along x-direction [L/t].

K_{yy} = principal hydraulic conductivity along y-direction [L/t].

Directional anisotropy in permeability was not implemented in the modeling of the north boundary alluvial aquifer. In a water table aquifer, the saturated thickness is used to calculate the transmissivity in an iterative fashion. This process has the effect of decreasing transmissivity in proportion to drawdown. A more complete description of the governing equations is provided in Appendix A, Section 1.4.

Basic Assumptions

The following assumptions within the model are valid for regional groundwater flow:

a. The flow is essentially horizontal in a two-dimensional plane. This assumption is valid when the variation of thickness of the aquifer is much smaller than the thickness itself. This approximation fails in regions where the flow has a vertical component.

b. The fluid is homogeneous and slightly compressible.

c. The aquifer is elastic and generally nonhomogeneous and anisotropic. The consolidating plastic medium deforms during flow due to changes in effective stress with only vertical compressibility being considered.

d. For the two-dimensional horizontal flow assumption, an integrated potentiometric level is used where the value is determined along vertical lines extending from the bottom to the top of the aquifer.

e. Within each element, parameters such as transmissivity, and storage coeficient are assumed to remain constant within each time step.

Method of Solution

The Galerkin finite element technique is used to simultaneously solve for flow and potentiometric head within the model. The direct method of solution of the simultaneous equations of flow are used to avoid errors associated with iterative methods. A detailed description of the method of solution is provided in Appendix A, Section 1.5.

Initial Boundary Conditions

To solve the equation, certain additional conditions imposed by the physical situation at the boundaries are selected. In general, for flow through an aquifer, three different boundary conditions are applicable:

1. Known potentiometric level on the boundary;

2. Known flux on the boundary; and

3. Known potentiometric level and its normal derivative on the boundary.

Any of the above boundary conditions or their combinations may appear in the modeling.

At the initial time, either the potentiometric surfaces are known in the entire domain or the hydrologic stresses (such as pumping and recharge) are specified and boundary conditions are known. For the second case, the system has reached the steady-state condition; therefore, the initial potentiometric surfaces can be found by solving Equation (1), while setting $\partial\phi/\partial t$ equal to zero. A more complete description of the initial and boundary conditions may be found in Appendix A, Section 1.4.3. The accuracy, limitations and restrictions of the model are detailed in Appendix A, Section 1.6.

3.2 MODEL INPUT DATA REQUIREMENTS

To solve Equation (1), the hydrodynamic parameters and stresses must be specified, and initial and boundary conditions assigned. The required input data to solve the regional groundwater flow in an aquifer follow:

- Type of Aquifer
- Static Potentiometric Surface
- Pumping Rate
- Hydraulic Conductivity
- Thickness of Aquifer
- Storage Coefficient
- Boundary Conditions

Along with the above information, any expected alterations in the groundwater flow regime (such as lowering the potentiometric surface) should also be incorporated into the model.

3.3 MODELING PROCEDURE

Grid System Development

The region around the RMA's north boundary was divided into grids of quadrilateral and triangular elements as shown in Figure 7. This grid system consists of 392 elements and 437 nodes. To increase the utility of the model as a design tool, the grid mesh is finer in the area of the north boundary containment system. The grid size was expanded in areas of sparse data and near the boundaries. Input data were prepared predominantly in the form of overlay maps. Discrete values for the various parameters were coded into the model at each element.

Type of Aquifer

As discussed in Chapter 2.0, the aquifer of concern in the north boundary area consists of a shallow, unconsolidated alluvial aquifer. Depending on the location, this aquifer acts as a phreatic or water table aquifer with locally confined areas. The areas where the potentiometric surface rises above the top of the main productive unit typically do not react strictly as a confined aquifer due to the silty nature of the overlying units. The typically lenticular nature of the aquifer causes this aquifer to respond as a semi-confined aquifer during short-term stress and as a water table aquifer after a longer period of time. Recharge to the aquifer is primarily due to leakage from surface water bodies. Areal recharge due to infiltration of precipitation is assumed to be negligible due to the semi-arid nature of the climate. The lower boundary of the alluvial aquifer is assumed to be impervious relative to the alluvium.

Boundary Conditions

Two types of boundary conditions were assumed around the periphery of the finite element grid system, namely either a constant head boundary or a no flow boundary. Figure 7 illustrates the location where both of these boundary types were used. Constant head boundaries were imposed at the upgradient ends of the alluvium filled paleovalleys that feed the north boundary alluvial aquifer. Additional constant head areas were set at the downgradient end of the grid system to simulate regional outflow.

Physical boundaries of the alluvial aquifer, generally associated with pinchouts over bedrock highs reported by Robson (1976), were treated as no flow boundaries. The net effect of this set of boundary assumptions is to simulate regional inflow from the south and outflow at the north end of the grid system.

Hydrodynamic Parameters

The hydrodynamic parameters of the aquifer system utilized in the final computer runs presented in this section are as follows:

Unit	Permeability (ft./day)	Storage Coefficient
Impermeable areas	0.1	.10
Silty sands (SM)	53.47	.10
Sands and gravel (SPGP)	401.05	.10
Slightly silty sands (SMSP)	200.52	.10

These permeabilities were based on evaluations of the results of the two field aquifer testing programs cited in Section 2.0, interpretation from boring logs, analysis of grain size curves, and the result of interactive model calibration.

The effective thickness of the aquifer is based on the calculated difference between the bedrock elevation and the potentiometric surface within an element and is updated during each time step. The values for saturated thickness were checked by the program so that saturated thickness does not exceed the thickness of the potentially productive aquifer. The values used for bedrock elevation and aquifer thickness were presented in Section 2.0.

3.4 COMPUTATION METHODOLOGY

The initial model calibration and computation of steady state potentiometric levels were conducted to assess the accuracy of the model. Initial estimates of permeability within each of the zones identified in Figure 5 were based on the field testing data available. The constant head boundaries were set at the observed values from the

potentiometric surface maps shown in Figure 6. The model was then executed to obtain steady state conditions with the resulting calculated potentiometric surface being compared to the observed values. Permeabilities were adjusted and the steady state potentiometric levels were recalculated. This calibration proceeded in an iterative fashion until the agreement between calculated and observed levels was judged to be adequate. The final steady state calculated potentometric level map is shown in Figure 8. The general agreement between calculated and observed potentiometric levels is adequate for purposes of evaluation of well field design and total flux in the aquifer across the RMA's north boundary. Some of the details of the potentiometric surface are not duplicated, particularly in the southwest quadrant of the grid network where gradients are low. The steady state levels shown in Figure 8 were used as the initial conditions in subsequent model runs; therefore, the groundwater system began in a state of equilibrium for design evaluation.

Steady state flows across the containment system area were evaluated using the computer model. The y component of flow was calculated for each element across the grid system (element numbers 178 through 198, shown in Figure 7 using the relationship $q = \frac{\partial \phi}{\partial y}$. This equation was numerically evaluated at the center of each element and when multiplied by the element width, the total flow was estimated. The flow rates by element are summarized in Table 1.

Simulation of the containment system was based on the proven design concept demonstrated during operation of the pilot containment system. This design consists of the following:

- o A slurry wall to block the flow of groundwater;
- o Dewatering wells located in the upgradient direction, and
- o Injection wells located in the downgradient direction.

The objective of this system is to operate with as little overall impact on water levels as possible. This condition is accomplished by operating the well field so that the quantity of water pumped is equal to that which would normally flow across the boundary if no barrier were present.

The presence and operation of this system was simulated by changing the permeability of one row of elements to a very low value along a line corresponding to the current alignment of the pilot system wall. Wells were simulated 300 feet upgradient from the wall with pumping rates equal to the computed steady state flux within each element. A similar setup was established downgradient from the wall for the recharge wells. Operation of this system was simulated for a period of 300 days using a time step of 10 days for accuracy. The resulting average potentiometric surface configuration is shown in Figure 9. The levels represented in this figure are averages within each element. The levels within the dewatering wells themselves will be somewhat lower. In the recharge wells, the levels will be higher than shown. At distances of about 150 feet from the wells, however, Figure 9 is representative of anticipated conditions.

3.5 TOTAL QUANTITIES OF CONTAMINANTS TO BE TREATED

A contoured concentration map of fluoride has been generated. The data for this map was provided by RMA personnel. This F^- map was prepared using data collected during May to August 1979 and contained in the Material Analysis Laboratory Report submitted to the Geohydrology Division, September 21, 1979. Concentrations on the map represent the results for samples collected after the pilot plant began operation on July 28, 1978. The concentration

data for fluoride was plotted at the appropriate borehole locations (Figure 3). This information was then contoured using linear interpolation between known data points. Variance to the linear interpolation procedure occurred only in a few localized instances where a temporal comparison with other maps of the same contaminant suggested a more realistic contour location. Groundwater dispersion of chemical species is not expected to be a linear function. Therefore, contours located in areas of sparce data may not represent actual concentrations in that area. However, in most cases, the amount of data available is enough to insure reliable conclusions.

The resulting contoured map (Figure 10) reveals that there are three high concentration areas. One high is centered at the base of the western bedrock high. The other two highs are located slightly to the east. The concentration contours have a west to east trend (high to low). Over 60 percent of Section 24 has a concentration of <2 mg/ℓ. Relatively low concentration areas exist in areas of high DCPD and DBCP concentrations. This result probably indicates that much of the fluoride has been removed by the large flow of groundwater through these areas. The operation of the pilot containment system has had little effect upon the location of fluoride concentration bands.

Figure 10 was generated using data collected during May to August 1979. Maps were also generated using data collected during the winter months (October and December 1978). These maps were evaluated for comparative purposes and are not included in this report. The general trends and locations of the contours were again similar. In most cases, the seasonal variations in fluoride concentrations were minimal. However, certain locations reveal large differences: Borehole 168, winter = .68 mg/ℓ fluoride, summer = 4.6

mg/ℓ fluoride; and Borehole 559, winter = 0.36 mg/ℓ fluoride, summer = 1.5 mg/ℓ fluoride.

Calculation of Quantities of F^- to be Processed

The concentration in the center of Elements 178-198 was estimated from the contoured concentration maps (Figure 10) for F^-. Flow rates used in calculational loadings were derived from the steady state model results described in Section 3.0. The center of these elements are located approximately 200 feet upgradient from the location of the dewatering wells in the pilot system. Therefore, the recovery values calculated will predict the recovery after operation has started and equilibrium is reached. The pumping rate for each element is also known; therefore, the total weight of F^- contained in the water can be calculated. These values are provided in Table 2. Approximately 6.6 kg of fluoride ion (F^-) will be handled each day. This corresponds to an expected average concentration in all elements of 2.72 mg/ℓ. Because of the large amount of data available, the weights of F^- processed should be fairly accurate.

Changes in the Quantities

Contour maps of the total area of Sections 23 and 24 were generated so that any future alternation in the concentrations of the contaminants could be predicted. Basically, the contour lines run parallel to the water flow. Therefore, concentrations will vary little with time. However, there will be an overall decrease in the concentrations as the aquifer is flushed. Where contour intervals run east and west, the

upgradient value is generally lower, therefore the overall concentrations will probably decrease.

TABLE 1

STEADY STATE FLOWS ACROSS THE NORTH BOUNDARY

Element Number(1)	Flow Rate(2)
178	3
179	14740
180	32105
181	36287
182	27400
183	23043
184	42347
185	33542
186	42354
187	39676
188	41045
189	45780
190	39856
191	34279
192	30774
193	66246
194	63284
195	25632
196	0
197	0
198	0
TOTAL FLOW RATE	638393

NOTES:

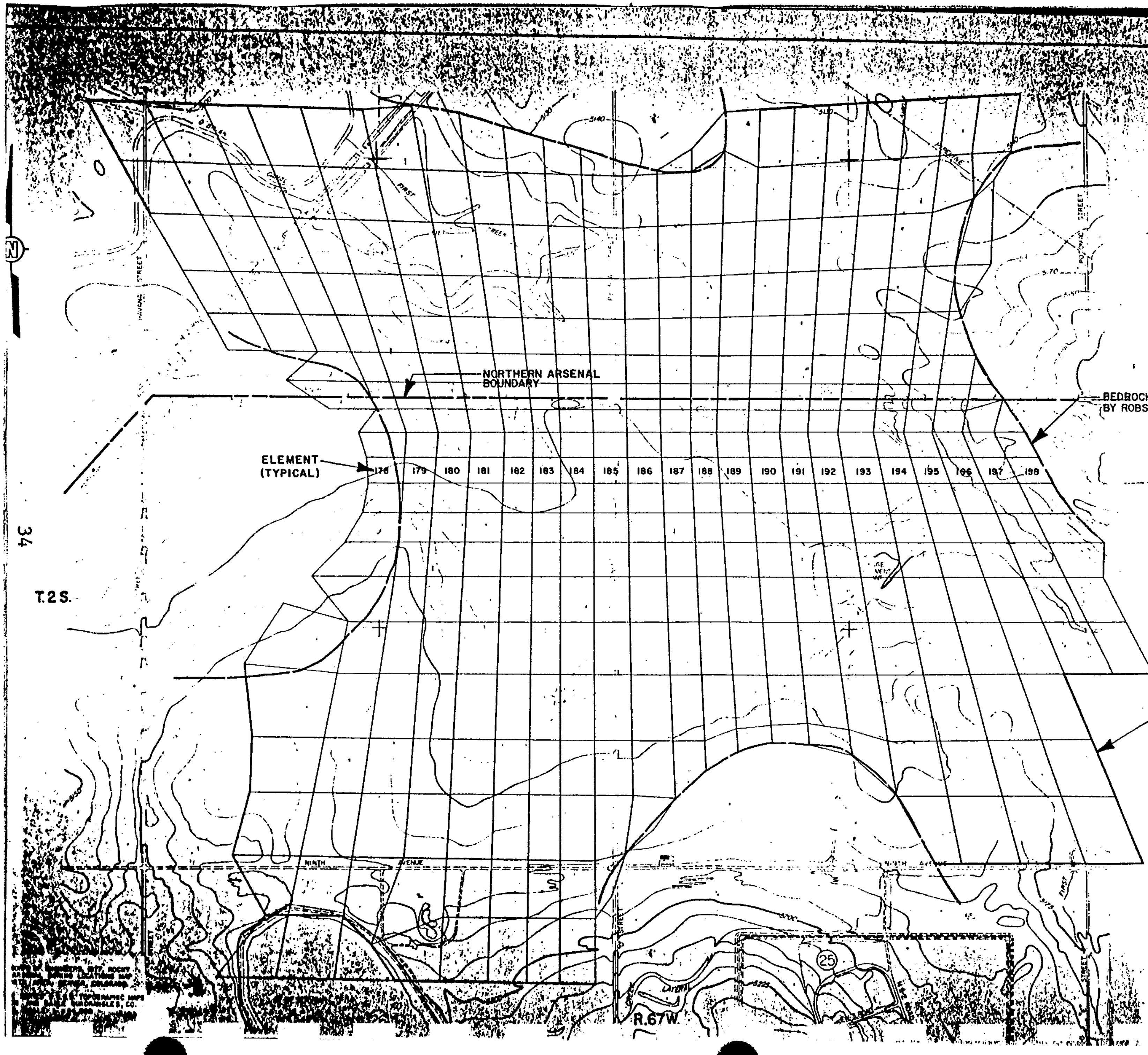
(1)See Figure 7 for locations of elements.

(2)Flow rates reported in gallons per day (gpd)

TABLE 2

TOTAL QUANTITIES OF FLUORIDE TO BE PROCESSED

ELEMENT NO.	FLOW RATE (GPD)	CONCENTRATION F- (mg/ℓ)	GRAMS/DAY F-
178	3	4.4	0
179	14740	5.4	301
180	32105	5.6	681
181	36287	3.8	522
182	27400	4.0	415
183	23043	4.5	393
184	42347	4.7	753
185	33542	4.1	521
186	42354	3.4	545
187	39676	2.9	436
188	41045	2.6	404
189	45780	2.4	416
190	39856	2.1	317
191	34279	1.8	234
192	30774	1.4	163
193	66246	1.0	251
194	63284	0.7	168
195	25632	0.5	49
196	0	0.5	0
197	0	0.7	0
198	0	1.0	0
TOTAL	638393		6566



SCALE
500 0 500 1000 FEET

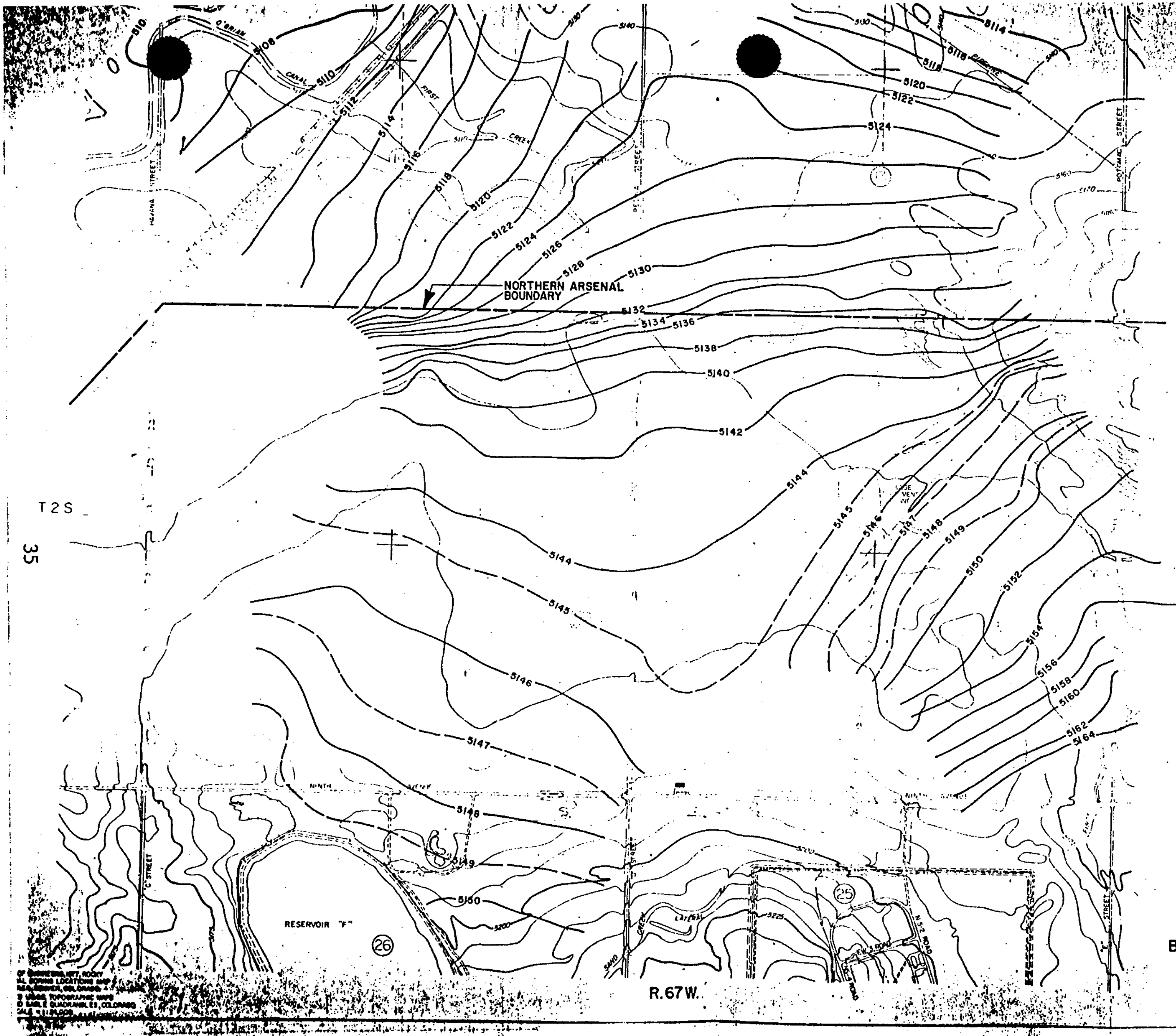
FIGURE 7

FINITE ELEMENT GRID SYSTEI

NORTH BOUNDARY CONTAINMENT SYSTEI
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PREPARED FOR

BATTELLE COLUMBUS LABORATO
COLUMBUS, OHIO



LEGEND

—5144— STEADY STATE POTENTIOMETRIC SURFACE ELEVATION CONTOUR

--5149-- INTERMEDIATE POTENTIOMETRIC SURFACE ELEVATION CONTOUR

SCALE

500 0 500 1000 FEET

FIGURE 8

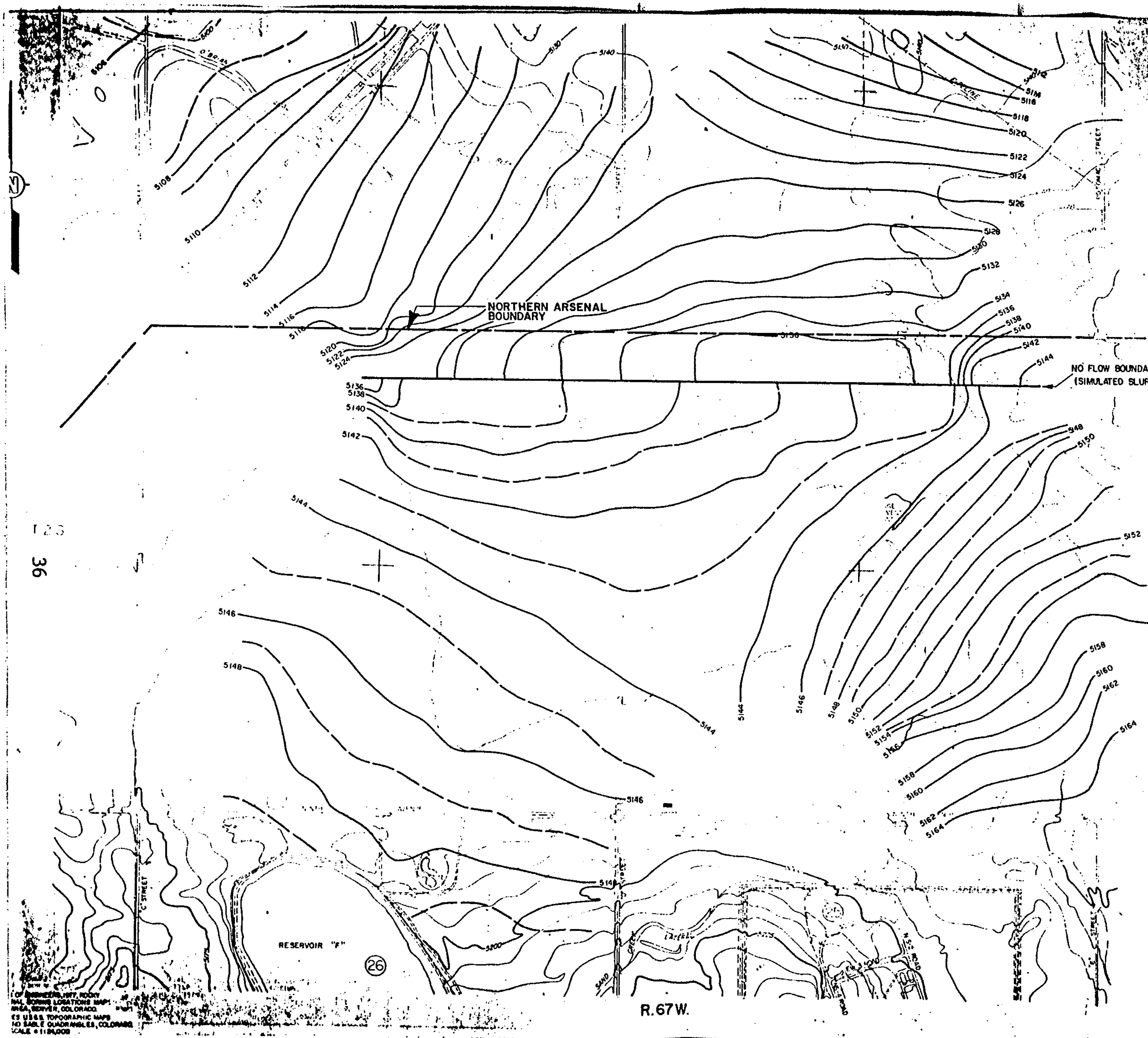
SIMULATED STEADY STATE POTENTIOMETRIC SURFACE FOR ALLUVIAL AQUIFER

NORTH BOUNDARY CONTAINMENT SYSTEM
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PREPARED FOR

BATTELLE COLUMBUS LABORATORIES
COLUMBUS, OHIO

D'APPOLONIA



LEGEND

5120 — POTENTIOMETRIC SURFACE CONTOURS

— — INTERMEDIATE POTENTIOMETRIC SURFACE CONTOURS

NOTE:
WATER LEVELS ARE AN AVERAGE BY NODE AND DO NOT REFLECT LEVELS AROUND EACH DEWATERING OR RECHARGE WELL

SCALE
500 0 500 1000 FEET

FIGURE 9

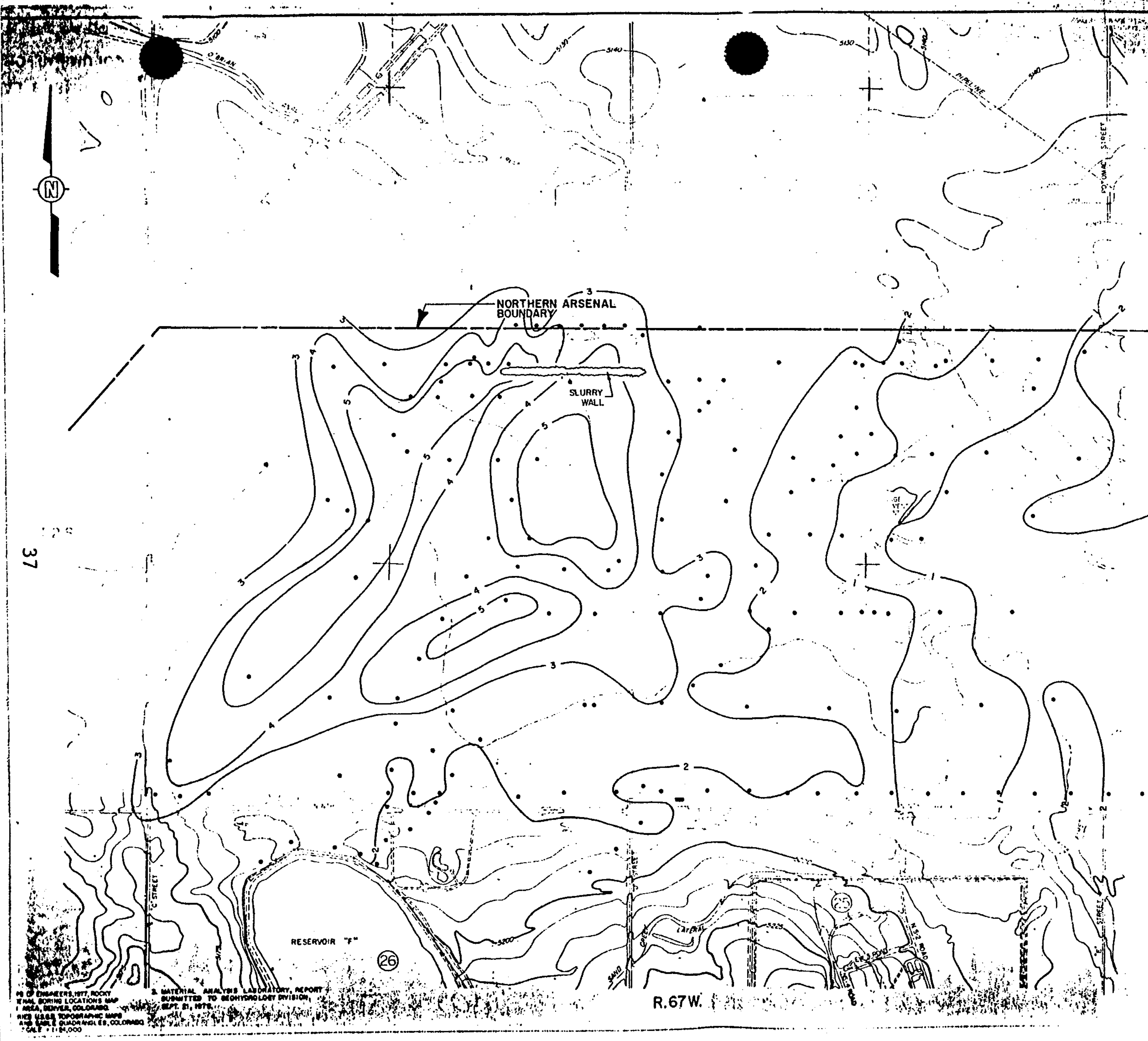
SIMULATED POTENTIOMETRIC SURF
AFTER 300 DAYS OF
SYSTEM OPERATION

NORTH BOUNDARY CONTAINMENT SYSTEM
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PREPARED FOR

BATTELLE COLUMBUS LABORATOR
COLUMBUS, OHIO

D'APPOLONIA



LEGEND

—2— FLUORIDE CONCENTRATION IN MILLIGRAMS/LITER (mg/L)

• — BOREHOLE/WELL LOCATION (WHERE DATA WAS AVAILABLE)

NOTE

CONTOUR LINES SHOWN ARE INTERPOL BETWEEN KNOWN POINTS AND MAY NOT REPRESENTATIVE OF ACTUAL CONDITIONS WITH SPARCE DATA. CONTOUR LINES ARE ON DATA COLLECTED FROM MAY - AUGUS WHERE MULTIPLE SAMPLE WERE AVAILAI THE VALUES WERE AVERAGED.

SCALE 500 0 500 1000 FEET

FIGURE 10

FLUORIDE CONCENTRATION MAI POSTSYSTEM

NORTH BOUNDARY CONTAINMENT SYSTEM
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

PREPARED FOR

BATTELLE COLUMBUS LABORATOR
COLUMBUS, OHIO

D'APPOLONI

BIBLIOGRAPHY

Bear, J., 1972, Dynamics of Fluids in Porous Media, American Elsevier Publishing Company, Inc., New York.

Pinder, G. F. and E. O. Frind, 1972, Application of Galerkin's Procedure to Aquifer Analysis, Water Resources Research, 8(1), pp. 108-120.

Robson, S. G., 1976, "Digital Model Study of Ground Water Contamination by DIISOPROPYLMETHYLOPHOSPHONATE (DIMP) Rocky Mountain Arsenal near Denver, Colorado," Final Report to U.S. Dept. of the Army, Rocky Mountain Arsenal, U.S. Geol. Survey Administrative Report.

4.0 ASSESSMENT B: US Army Toxic and Hazardous Materials Agency

To determine the expected contaminant loading of a compound within a controlled section of aquifer, a mass flux computation was formulated. By knowing total groundwater flow and total contaminant mass migrating per unit time in any section of aquifer, a concentration prediction can be made. This technique addresses variable aquifer characteristics such as cross sectional area (saturated thickness and length), potentiometric gradient and aquifer permeability.

4.1 MASS FLUX DESCRIPTION

The computer program used in this study utilizes a two-dimensional representation of an aquifer to model groundwater flow characteristics. The basic equation uses a form of Darcy's law for the flow of water through a porous media. To compute the contaminant mass flux for the north boundary alluvial aquifer, a transect perpendicular to the northward flowing groundwater was established and divided into a series of rectangular elements. Each element was then described with appropriate geohydrologic terms to thoroughly define its flow characteristics. Past contaminant concentration data was assessed to determine a representative concentration value for that section of aquifer. Input of this information for every element yielded a composite mass flux estimate. A full description of the software input/output requirements is contained in Appendix B. A summary of the governing equation, assumptions made and data used in the program follows.

Governing Equation

The mass flux computation uses a combination of groundwater flow quantity (volume per time) and contaminant concentration profile (weight per volume) to calculate contaminant mass movement (weight per time). A form of Darcy's law for the flow of groundwater forms the basis of the mass flux flow estimate. The governing equation thus can be represented by:

$$\emptyset = KLtI \times C \times U \qquad (3)$$

where:

$\emptyset$ = mass flux across a transect in gms/day

K = permeability of saturated zone in feet/day

L = saturated length in feet

t = saturated flow thickness in feet

I = gradient of the water table

C = contaminant concentration in mg/liter or ug/liter

U = units' adjustment

Basic Assumptions

The following assumptions are necessary:

a. The flow is essentially horizontal in a two-dimensional plane. This assumption is valid when the variation of thickness of of the aquifer is much smaller than the thickness itself. This approximation fails in regions where the flow has a vertical component.

b. The fluid is homogeneous and slightly compressible.

c. For the two-dimensional horizontal flow assumption, an integrated potentiometric level is used where the value is determined along vertical lines extending from the bottom to the top of the aquifer.

d. Within each element, parameters such as cross-sectional areas, permeability and potentiometric gradients are assumed to remain constant. This assumption dictates that the aquifer under consideration is at steady state.

4.2 MASS FLUX INPUT DATA REQUIREMENTS

To solve Equation (3), the groundwater flow characteristics must be specified for a section of aquifer and initial boundaries assigned for the contaminant concentration assessment. The required input data to solve the mass flux computation follow:

- o Transect Specifications
- o Potentiometric Gradients
- o Aquifer Cross-sectional Area (Saturated)
- o Aquifer Permeability
- o Contaminant Concentration Assessment

ual input values with rationale for each of these areas is described in the following subsections.

Transect Specifications

Because of the assumption of two-dimensional flow, the transect through which the mass flux is to be computed must be specified perpendicular to the predominant groundwater flow direction. Intervals along the transect are chosen to define sides of the various rectangular elements in which groundwater flow will be calculated. The larger the number of intervals along a transect, the greater the mass flux refinement can be. However, directly associated with this increase in intervals is the enlargement of geohydrologic data needed to define each aquifer element.

For the situation of the north boundary of RMA, a two mile transect parallel to the north boundary was chosen for analysis (Figure 11). This transect lies approximately 500' back from the arsenal boundary (in line with the pilot system) in the north part of sections 23 and 24. The transect was subsequently divided into 250' intervals which resulted in approximately 40 equally spaced aquifer units. Groundwater flow in this area is at perpendicular direction to the boundary.

Potentiometric Gradients

Aquifer gradients must be established for each transect interval. Potentiometric gradients represent the driving force for the groundwater system.

Historical water level data was reviewed to determine possible long-term trends in a alluvial aquifer. New borings and piezometers were located to fill gaps in the existing boring and piezometer array. Data from the logs and piezometers were used to determine water table elevations, base of alluvial aquifer and groundwater flow patterns. A general overview of this data has been previously highlighted in Section 2: Site Hydrogeology. Specific hydrodynamic parameters for input in the mass flux computation for the north boundary area is presented below:

a. Water table measurements were taken in the study area in October-November 1978 and, upon completion of the installation of new piezometers, arsenal-wide measurements were taken in March-April 1979 and in May-June 1979. The three sets of water table measurements were reviewed. Water table fluctuations during the relatively short period of this May-June 1979, was constructed (Figure 6b).

b. The water table contours show three spacing and direction patterns. The first pattern occurs in the western part of the study area (section 23) and is characterized by widely spaced contour lines (low gradient) that trend to the northeast. The second pattern occurs in the eastern part of the study area (sections 24 and 19). This pattern is characterized by closely spaced contours trending in a northwest direction. About 1200 feet south of the north boundary, the first and second patterns converge to form closely spaced contour patterns that trend in a northernly direction.

c. Potentiometric gradients in this area tend to the north with an average gradient of 0.007 ft/ft. Small variations in the gradient exist along the boundary as one proceeds from west to east. Estimates of this variability about 0.007 have been considered in the input parameters to the mass flux computation (Table 3).

Aquifer Cross-Sectional Area (Saturated)

ation 3 computes aquifer cross-sectional area by the multiplication of saturated length (l) times saturated flow thickness (t). This information must be specified for each transect interval.

Borings placed in the north boundary vicinity have gathered geotechnical data to define aquifer media characteristics. Previous boring locations and logs were reviewed and a boring and sampling program was designed to fill data gaps in sections 23,24,25 and 26 and to evaluate potential pollution migration in sections 19,23,24,25 and 26. Seventy-five new borings (Nos. 900-974) and borings 378-380, 382, 385, and 533 were located to supplement the existing boring data. Split-spoon samples were obtained at 5 feet intervals and at stratum changes, where possible, from each boring. Samples were field classified on site by several inspectors. Laboratory classification was performed on

selected soil samples. Monitoring wells were installed at all new boring locations for water level measurements, water sampling, and permeability tests.

All available logs and water depth readings from piezometers were used to construct the base of the alluvial aquifer (Figure 4), saturated thickness (Figure 5) and water table (Figure 6a and b) maps presented in section 2.0. The cross section at the north boundary is shown in Figure 12. On the plate, two types of data are presented--one cross section contains general soil types and water levels and below it another cross section presents the stratigraphy. Specific hydrodynamic parameters for input in the mass flux computation for the north boundary area is presented below:

a. Base of the alluvial aquifer is presented in Figure 4. The map generally depicts the weathered shale surface of the Denver formation which underlies the alluvium but includes the Denver formation sands where they are in direct contact with the alluvium. This lower boundary is assumed to be relatively impervious. The general slope of the base of the alluvial aquifer is to the north-northeast north of Basin F and north-northwest in section 24. These slopes dictate the flow of alluvial groundwater.

b. Figure 5 is an isopach map showing the saturated thickness of the alluvial aquifer which includes Denver sands that are in contact with the alluvium. The map reflects saturated thicknesses based on the differences between the base of the alluvial aquifer surface and piezometer surface. Figure 5 presents all saturated sediments which includes fine-grained materials of relatively low permeability. As expected, areas of greatest saturated thicknesses follow channels and the areas of least saturated thicknesses generally coincide with the Denver formation highs.

c. The mass flux transect of interest (cross section represented in Figure 12) is just south of, and parallel to, the north boundary and cross sections 23 and 24; the section is perpendicular to the northernly flow of groundwater in the alluvial aquifer. This section identifies the base of the alluvial aquifer as weathered Denver shale except for two areas which are identified later. Denver High "A" occurs near the center of the western half of the

cross section and is the northernly extension of the Denver High "A" in cross section B-B'. West of the Denver High "A" the Denver surface decreases in elevation and contains two small channels. Between these two channels, the Denver formation consists of silt and clayey sand. East of the High "A" is one small, narrow channel and one shallow, wide channel followed by a wide, flat surface extending across the boundary of sections 23 and 24. The center of section 24 has one large channel (identified in Figure 12 as channel 1) with two smaller channels to its west. The Denver formation between the channels consists of silty and clayey sands. East of channel 1 the Denver surface rises rapidly and forms the Denver High "D". The Verdos sands and gravels, west of the Denver High "A," are from 0 to 10 feet thick and thicken to the west. East of the Denver High "A" the Verdos alluvium reappears and ranges in thickness from 5 to 20 feet with thickest deposits occurring in the channels. With the exception of the Denver High "A," coarse to fine gravels appear intermittently throughout the alluvium. Overlying the Verdos sands and gravels are clays, fine sands, and silts ranging in thickness from 5 to 20 feet. These sediments are in direct contact with the Denver formation where the Verdos is absent on the High "A." These soils consist of eolian sands and alluvium transported from higher elevations, except for the areas in and adjacent to the First Creek valley (center of section 24 in Figure 12) and the small valley west of the section 23 and 24 boundary where Piney Creek alluvial clays, silts, and sands occur.

d. From the preceeding information it has been determined that the north boundary alluvium is fully saturated from approximately the midpoint of interval 11 to just inside interval 35. Saturated thickness of this aquifer ranges from 1 to 22 feet. Exact cross sectional data used for input are delineated in Table 3.

Aquifer Permeability

Field pump tests and rising and falling head (slug) tests were performed in the study area to determine the coefficients of permeability of the alluvial aquifer. Specific hydrodynamic parameters for input in the mass flux computation for the north boundary area is presented below.

a. Field Pump Tests: Five pump tests were performed in 1978 by WES. Three tests were preformed north and northeast of Basin F in section 23 and two tests were performed in section 24. One test was southwest of the sewage lagoon and the other test was north of the sewage lagoon near the north boundary. Wells 345, 368, 529, 548, and 549 were used for the tests. Observation wells were installed on lines originating at the test well extending to 1000 feet away from the test well. During the pump tests water level changes in the observation wells were measured for drawdown and recovery and coefficients of permeability were computated using the drawdown and recovery rates. Coefficients of permeability computed from test wells 345, 368, and 529 ranged from 2400 to 12,000 gpd/ft^2 and the coefficients of permeability on the observation well lines ranged from 3400 to 8200 gpd/ft^2. These wells are in, or adjacent to, a subsurface channel which runs northeast from north of Basin F towards the north boundary. Well 548, located astride a small ridge-like area, had a coefficient of permeability of 1100 gpd/ft^2; coefficients of permeability on the observation well lines were from 1300 to 2000 gpd/ft^2. Well 549, located adjacent to Denver High "B" and in an area of rapid groundwater gradient changes, has a coefficient of permeability of 430 gpd/ft^2. The observation well lines reflected rapid changes in the coefficient of permeability when measured over a short distance (0-50 ft; 250 gpd/ft^2) as compared with a long distance (50-1000 ft, 1100 gpd/ft^2). These differences could be caused by the influence of the main channel at their extremities.

b. Rising and Falling Head Tests: The rising and falling head (slug) tests were conducted mainly in areas where no pump tests had been performed. Some testing was done west of the existing pilot plant and at other locations.

The slug test consists of placing a calibrated pressure transducer in a well to measure the water level in that well, removing (or injecting) a volume of water from (into) the well to change the water level in as nearly instantaneous a manner as possible and recording the recovery of the water level to its original value with the passage of time. The continuous record of water level versus time is then plotted as the ratio of measured head of water in the well to the initial head of water upon withdrawal (or injection) at time zero

(called the "recovery ratio" or H/H_o) versus the logarithm of elapsed time in seconds. The curvilinear graph is then matched to a previously calculated family of theoretical surveys that includes the variables of coefficient storage, transmissibility, permeability, and confining conditions.

Upon successfully matching the field data plot to one of the theoretical type curves, the nature of aquifer confinement is identified by the shape of the curve and the value of " " for the matched curve. Also the value of time is noted on the data plot which coincides with the time of 1.0 sec on the theoretical type curve.

If the groundwater response in the aquifer during the short period of the test and for the small volumes involved indicates unconfined conditions, then the proper type curve can be matched so that a value of the coefficient of permeability can be obtained from the equation:

$$k = \ell n \left(\frac{R_e}{r_w} \right) \frac{1}{2L} \frac{r_w^2}{t_1} \qquad (4)$$

where

k = coefficient of permeability $(L^3/T/L^2)$

R_e = radius of influence of the test (L)

r_w = radius of well (equal to radius of screen in all of the RMA tests (L)

L = screen length (L)

t_1 = time value on data plot coinciding with t = 1.0 sec (T)

For fully penetrating wells:

$$\ell n \left(\frac{R_e}{r_w} \right) = \left(\frac{1.1}{\ell n \left(\frac{H}{r_w} \right)} + \frac{C}{L/r_w} \right)^{-1} \qquad (5)$$

where

H = height of stable water level above bottom of screen (L)

C = value obtained from plotted results of electrical analog tests for a specific value of L/r_w (dimensionless)

For partially penetrating wells:

$$\ln\left(\frac{R_e}{r_w}\right) = \left(\frac{1.1}{\ln\left(H/r_w\right)} + \frac{A + B\ \ln\left(\frac{D - H}{r_w}\right)}{L/r_w}\right)^{-1} \tag{6}$$

where

D = height of stable water level above bottom of aquifer (L)

A = value obtained from plotted results of electrical analog tests for a specific value of L/r_w (dimensionless)

B = value obtained from plotted results of electrical analog tests for a specific value of L/r_w (dimensionless)

If the groundwater response in the aquifer during the short period of the tests and for the small volumes involved indicates continued storage conditions, then the coefficient of storage can be calculated from:

$$S = \frac{r_c^2}{r_s^2}\alpha \tag{7}$$

where

S = coefficient of storage of the aquifer (dimensionless)

r_c = radius of casing in interval of water level fluctuation (L)

r_s = radius of screen (L)

α = value obtained from type curve (dimensionless)

Transmissibility is calculated from:

$$T = \frac{r_w^2}{t_1} \tag{8}$$

where r_w and t were previously defined and coefficient of permeability is calculated from:

$$k = \frac{T}{L} \tag{9}$$

where T and L were previously defined.

The wells used for slug tests were 8 inch in diameter and were backfilled by pea gravel subsequent to placement of the piezometers and prior to sealing with cuttings. The piezometer risers and screens were 1.0 inch inside radius. Therefore, in the analyses with Equations 4, 5, 6, 7, and 8 it was assumed that $r_c = r_s = r_w = 1.0$ in. = 2.54 cm.

The screen lengths were used for the values of L in equations 4, 5, 6, and 9 were determined in the following way. A f-ft screen section was measured and found to consist of 85 percent of its total length comprising the slotted portion and the remainder of the total length being solid end sections and couplings Therefore, the screen lengths of each piezometer were multiplied by 0.85 to obtain the value used for L in that particular calculation. In a few instances, the screen sections extended into the lower Denver clay shale or aquiclude. In those instances the elevation differences between the tops of the screens and the aquiclude were used as the nominal screen lengths to which the 0.85 adjustment was applied. All the above assumptions and considerations have been applied to all previous slug test analyses from RMA piezometers as described. This procedure makes all the results of RMA slug test analyses internally and directly comparable, at least as far as the design, construction, and final configuration of the piezometers are comparable.

The bailer used at RMA for the slug tests had a nominal 2.0-liter capacity. This volume of extracted water caused an initial water level change of approximately 3.2 ft in the casing. Variations in the degree of filling the bailer coupled with water level recovery during the 1-2 sec allowed for surging and dribble-back resulted in the initial water level being up to 0.5 ft less than the masimum possible. The pressure transducer, together with the resolution of the continuous oscillographic recorder, provided a measured precision of ±0.01 ft head of water. Depending upon the time scale used for a particular test the precision in time measurements was either ±0.01 or ±0.10 sec with the latter most commonly used. The transducer and recorder were used for water level measurements from the initiation of a test to either its completion (judged to be 95 percent recovery) or 3000 sec elapsed time, whichever came first. If the test had not reached

completion in 3000 sec, then the M-scope water level detector was used at periodic intervals thereafter to completion. Each initial M-scope reading was made while the transducer data was still being recorded to provide a consistent date initial base. It was found that the M-scope data was reliable to about ± 0.05 feet of water level and the time reliability good to about ± 1 min.

c. Permeability values of the north boundary aquifer system utilized in the mass flux computation are as follows:

UNIT	PERMEABILITY (FT/DAY)
Impermeable areas	0.4
Silty sands (SM)	10-50
Slightly silty sands (SMSP)	200
Sands (SP)	300
Sands and gravel (SPGP)	600

These permeabilities are based on evaluation of the results of five pump tests and approximately 60 slug tests. Permeability values for each interval are summarized in Table 3.

Contaminant Concentration Assessment

Fluoride in groundwater at RMA has been limited to leakage of fluoride wastes from disposal basins and to desorption of fluoride from fluoride enriched natural soils. Since the government's contribution to an off-post migration problem has been unknown, wells were placed along the north boundary (example of spacial distribution is presented in Figure 13). Routine water quality samples from these wells have established Basin F as a major source of the groundwater pollution. Concentration data averaged over the years 1977 to 1979 was used as input to the mass flux computation. A select presentation of this fluoride concentration data along the north boundary (Figure 14) and an isoconcentration map for the entire north boundary vicinity (Figure 15) are discussed below.

a. Two areas containing fluoride concentrations in excess of 5 mg/ℓ are found. One area is located in the northeast corner of section 23. These two areas were probably connected at some time in the past and have been separated by groundwater movement. The concentration found in the center of section 23 is in an area of slow flow and the contaminants have remained somewhat stationary. The fluoride probably migrated into this area when groundwater elevations were higher.

b. There is a general distribution of fluoride above 2 mg/ℓ in wells located along the northern perimeter of Basin F, through most of section 23 and the western part of section 24, to the northern boundary. The highest concentrations of fluoride appear to be crossing the transect line to the west of the existing interim treatment system. No well defined plume was found exiting the northeast corner of Basin F which is surprising since Basin F liquid contains fluoride in concentrations in excess of 100 mg/ℓ. Several wells in section 24 east of the main area of contaminant distribution were found to contain fluoride concentrations above background levels. Several perimeter wells on the southwest corner of Basin F were found to contain fluoride in excess of 4 mg/ℓ indicating possible migration in that direction.

c. Although Basin F still appears to be the source of fluordie contamination in study area, the amount of fluoride leaching to the groundwater appears to be decreasing. The allowable flux as indicated on the flux diagrams will be shown to be very close to the actual flux.

3 MASS FLUX MODELING PROCEDURE

Groundwater flow through each aquifer interval is computed directly from geohydrologic data provided to the software as input. Contaminant concentration data is selected from the USATHAMA Data Management System according to an input selection routine. If the model determines that more than one well exists within an inteval, a weighted concentration average is used:

$$C_m = \frac{C_a N_a + C_b N_b}{N_a + N_b}$$

where:

C_m = mean concentration within interval

C_a, C_b = concentration at wells a and b

N_a, N_b = number of water quality values at well a and b

Appropriate multiplication of each interval's flow calculation with contaminant concentration data yields a computed mass flux. A mass flux curve

is generated when all the intervals are considered. If the user specifies a constant concentration value equal to the water quality standard as input, a comparison curve will be provided. This comparison flux can be used to:

a. Determine locations along the transect where the largest contaminant migration is likely.

b. Provide an insignt into the relative flow of groundwater across the transect.

Integration of the computed mass flux curve will yield an estimate of total contaminant release through the section of aquifer under consideration. Division of this estimate by the groundwater flow rate will result in a contaminant loading expectation expressed in concentration terms.

4.4 COMPUTATION METHODOLOGY

Geohydrologic definition cannot be firmly established. Various individuals may look at the same data base and make divergent interpretations. Because of this, a validation procedure for the mass flux model was used to ensure computation methodology accuracy.

An initial mass flux computation was conducted using idealized hydrodynamic parameters along the north boundary. Performance of the 1500 foot pilot containment/treatment system, which exists within intervals 15-21, was used for validation purposes. Actual influent flow rates and concentration loadings for the pilot system were compared to predicted values from the mass flux computation. Only slight modifications to the input parameters were needed to achieve an agreement within a 20 percent error. Resultant values for the validation run are shown below:

	EXPECTED FLUX	ACTUAL PERFORMANCE
Pilot System Influent Flow (gpm)	110(1)	30-60
Pilot System Influent Fluoride Concentration (mg/ℓ)	3.6	3.1-4.9

(1) NOTE: D'Appolonia (1979) examined performance of the pilot containment system over the first year of operation. It was concluded that the pilot system was effectively removing and treating approximately 30 percent of the groundwater flow in the 1500 foot aquifer interval intercepted by the system. An improper match between aquifer characteristics and dewatering well components has resulted in greater groundwater flows than the pilot dewatering wells could handle.

Once hydrodynamic input parameters were validated, the mass flux computation was utilized to assess contaminant migration potential and to perform various contaminant loading calculations. The following section expands on these assessments.

4.5 TOTAL QUANTITIES OF CONTAMINANT TO BE TREATED

Total flow across the north boundary has been estimated from geohydrologic data presented in Sections 2 and 4 at 882,200 gallons per day or 612 gallons per minute. This calculation agrees closely with Zebell's (1979) estimate 884,100 gallons per day. Integration of the resulting mass flux computation (Figure 16) reveals that approximately 7.8 kg of fluoride is contained in the north boundary alluvial flow (Table 4). This corresponds to an average concentration in all intervals of 2.3 mg/ℓ. High flow rates of relatively clean groundwater in the First Creek vicinity combined with low flow rates of contaminated groundwater from the Basin F area yield an expected composite stream to the expanded north boundary system just below the State of Colorado standard of 2.4 mg/ℓ. Because of the extensive water quality and geohydrologic data available for this assessment, the amount of fluoride to be processed should be fairly accurate.

Changes in the expected contaminant loading to the expanded treatment facility over several years of operation should be negligible. Fluoride concentration patterns at the north boundary have changed very little over the last few years of monitoring. Current contaminant contour lines lie parallel to the groundwater flow direction which will result in very little future water quality variation. In fact, upon initiation of source control asures, contaminant loadings at the north boundary expanded system will significantly lessen.

TABLE 3

FLUORIDE MASS FLUX INPUT PARAMETERS

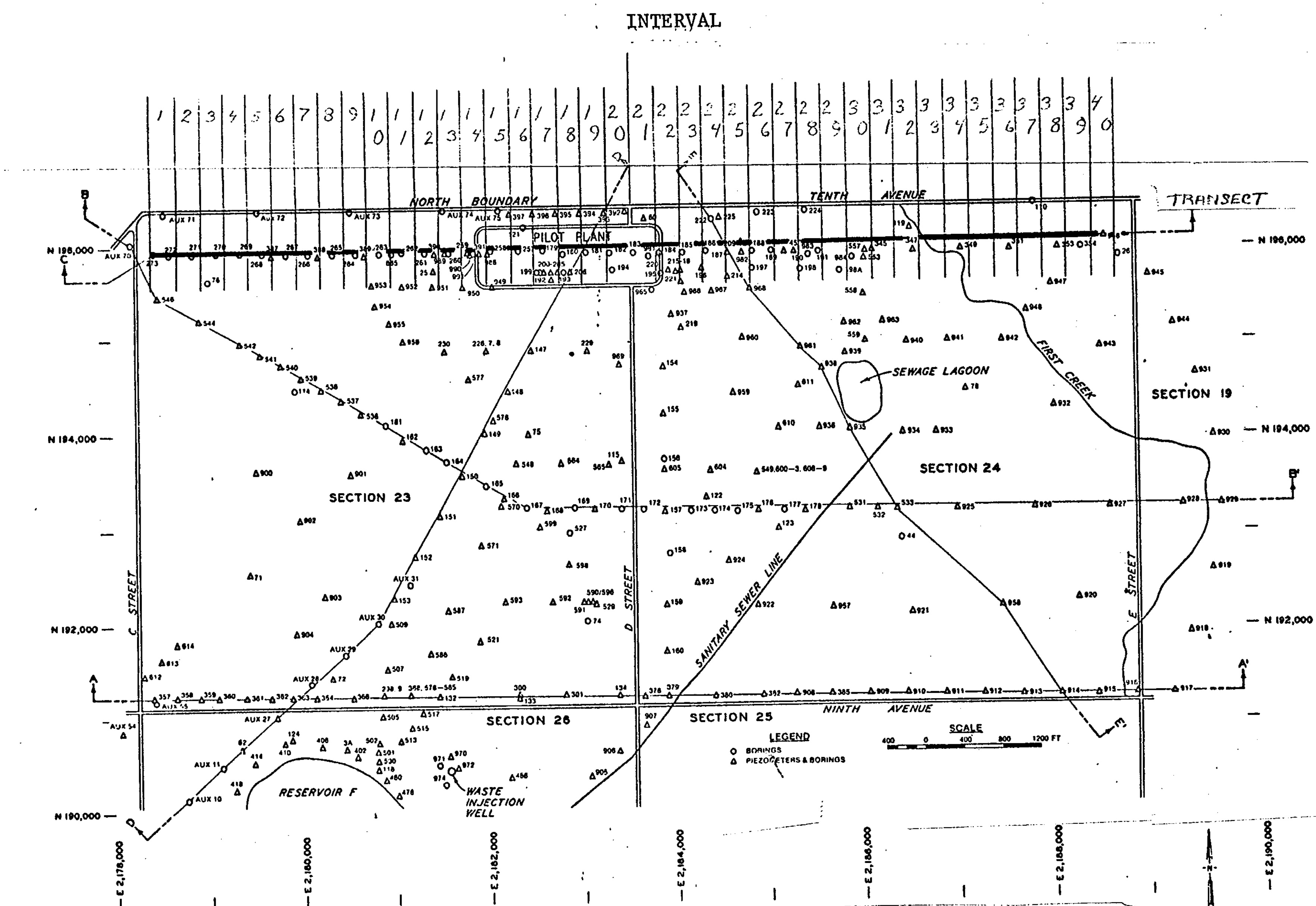
Transect Length	10,000 Feet
Interval Width	250 Feet
Water Quality Sampling Interval	1 Jan 77 to 4 Oct 79
Water Quality Standard	2.4 mg/ℓ

INTERVAL NO.	PERMEABILITY (FT/DAY)	GRADIENT (FT/FT)	THICKNESS (FT)	LENGTH (FT)
1	10.0	0	0	0
2	10.0	0	0	0
3	10.0	0	0	0
4	10.0	0	0	0
5	10.0	0	0	0
6	10.0	0	0	0
7	0.4	0	0	0
8	0.4	0	0	0
9	0.4	0	0	0
10	50	0	0	0
11	0.4	.0030	1.0	100
12	50	.0040	3.0	250
13	50	.0050	3.0	250
14	100	.0060	7.0	250
15	150	.0062	10.0	250
16	150	.0064	12.0	250
17	200	.0066	11.0	250
18	250	.0068	9.0	250
19	300	.0070	8.0	250
20	350	.0072	7.0	250
21	350	.0074	7.0	250
22	300	.0076	8.0	250
23	225	.0078	10.0	250
24	350	.0080	12.0	250
25	225	.0078	16.0	250
26	180	.0076	17.0	250
27	250	.0074	12.0	250
28	250	.0072	15.0	250
29	200	.0070	18.0	250
30	225	.0068	21.0	250
31	350	.0066	22.0	250
32	350	.0064	20.0	250
33	325	.0062	15.0	250
34	250	.0060	6.0	250
35	200	.0058	2.0	50
36	0.4	0	0	0
37	0.4	0	0	0
38	0.4	0	0	0
39	0.4	0	0	0
40	0.4	0	0	0

TABLE 4

TOTAL QUANTITIES OF FLUORIDE TO BE PROCESSED

INTERVAL NO.	FLOW RATE (GPD)	FLUORIDE MASS FLUX (GRAMS/DAY)
1	0	0
2	0	0
3	0	0
4	0	0
5	0	0
6	0	0
7	0	0
8	0	0
9	0	0
10	0	0
11	1	0
12	1120	10
13	1400	50
14	7850	90
15	17400	280
16	21550	340
17	27140	350
18	28500	390
19	31400	440
20	33000	340
21	33910	420
22	34110	370
23	32820	300
24	62830	650
25	52500	380
26	43380	410
27	42630	440
28	50490	450
29	47120	420
30	60100	400
31	95030	490
32	83650	370
33	56550	275
34	16850	125
35	869	10
36	0	0
37	0	0
38	0	0
39	0	0
40	0	0
TOTAL	882200	7790



F[illegible]gure [illegible] B[illegible]ng, [illegible]zom[illegible] and [illegible]ross [illegible]ection Locations

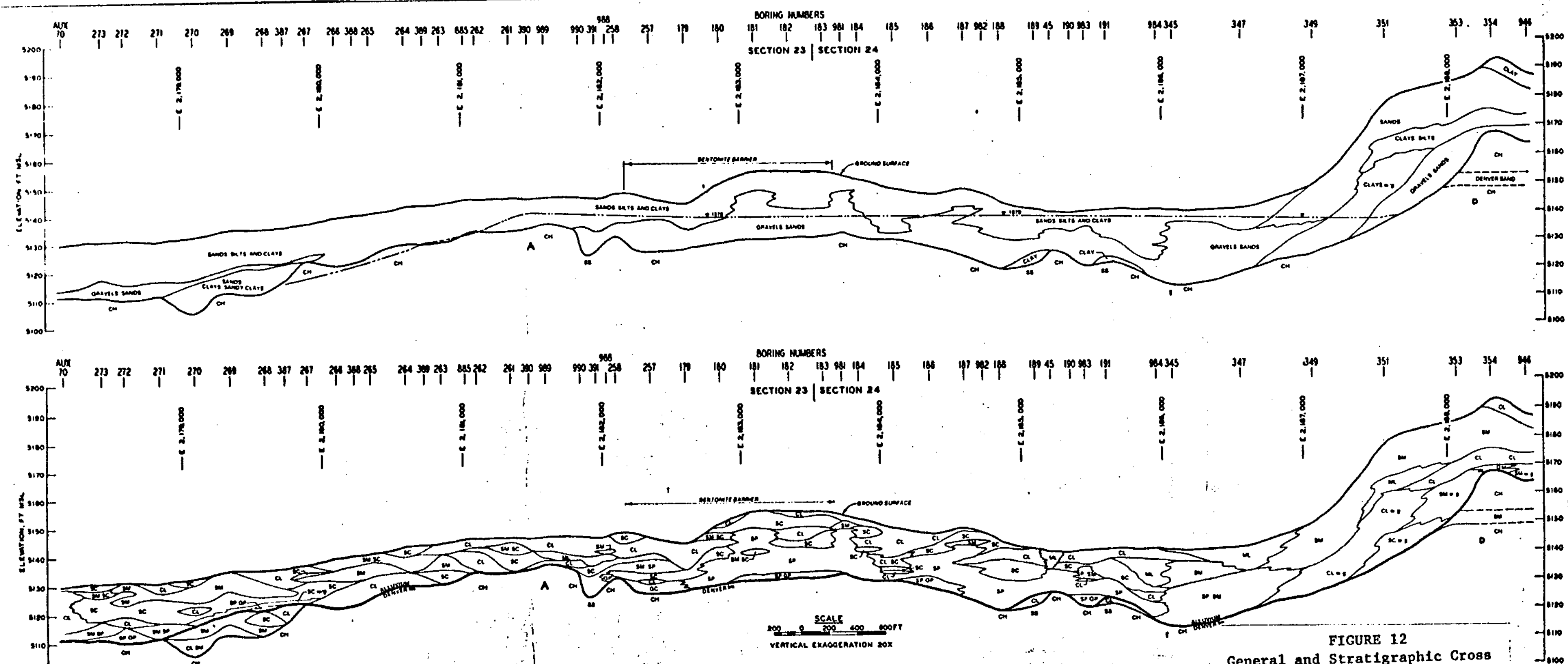


FIGURE 12
General and Stratigraphic Cross Section with 1979 Water Levels Along RMA North Boundary

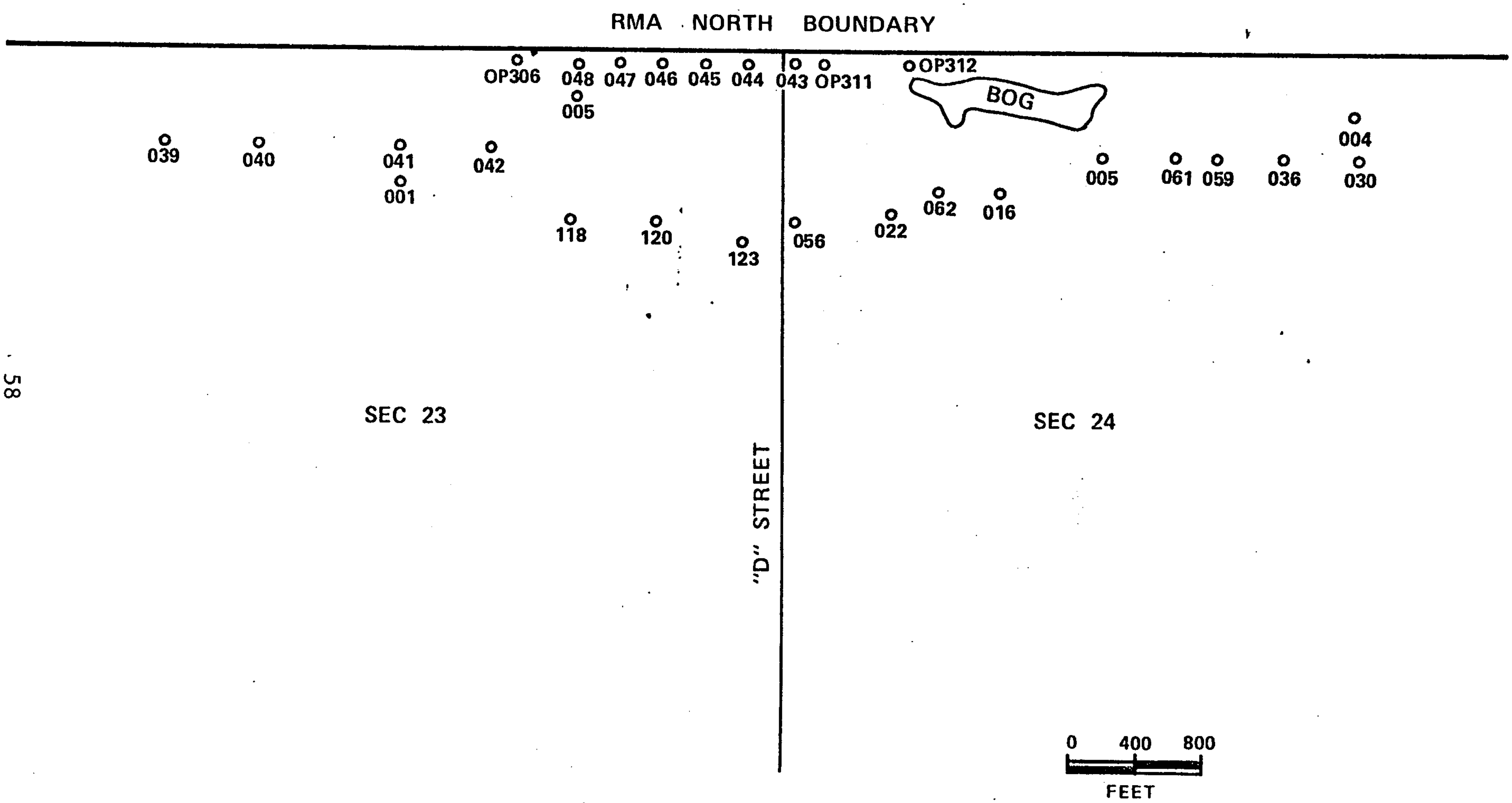


FIGURE 13 RMA NORTH BOUNDARY MONITORING WELLS

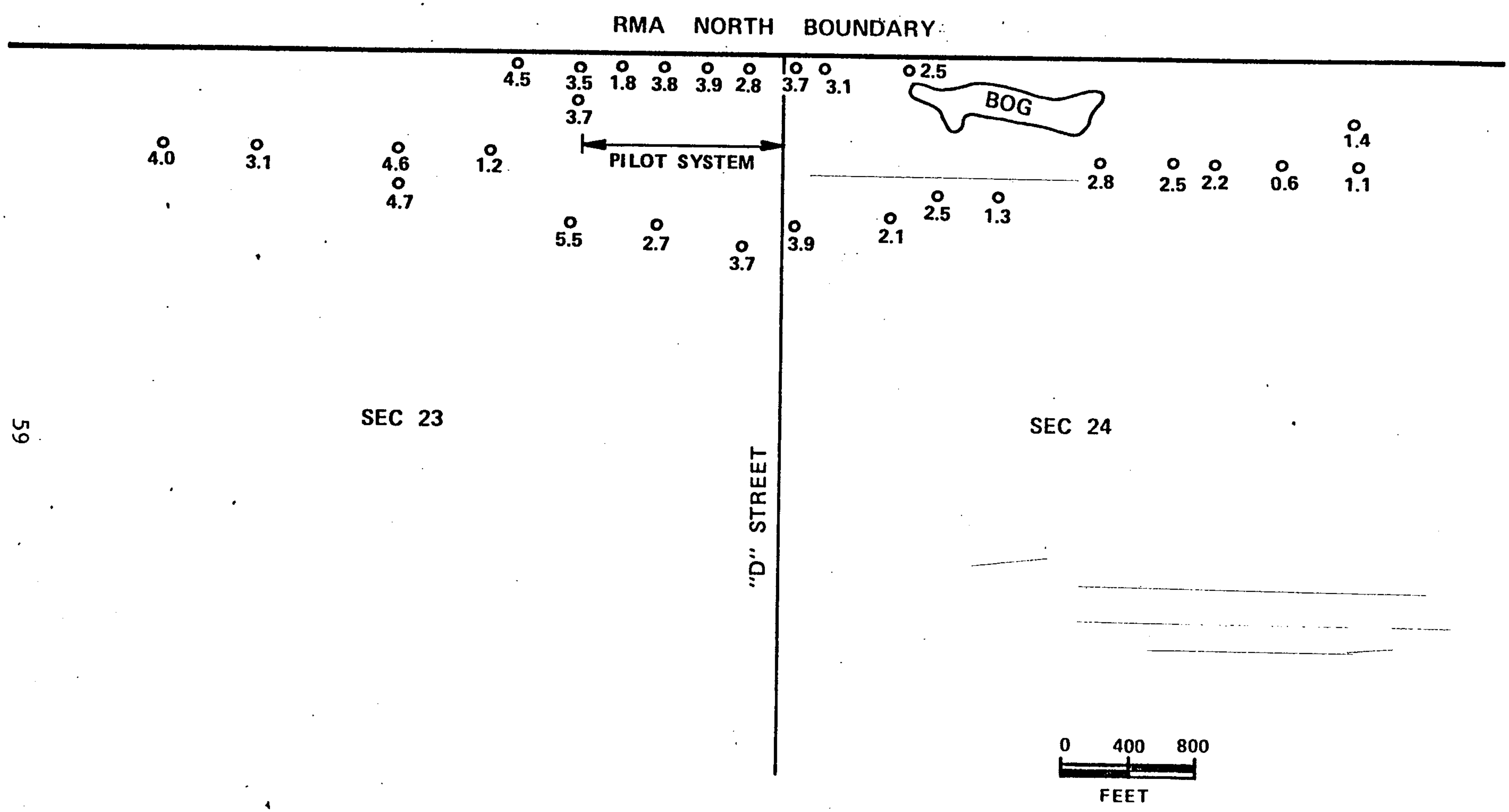
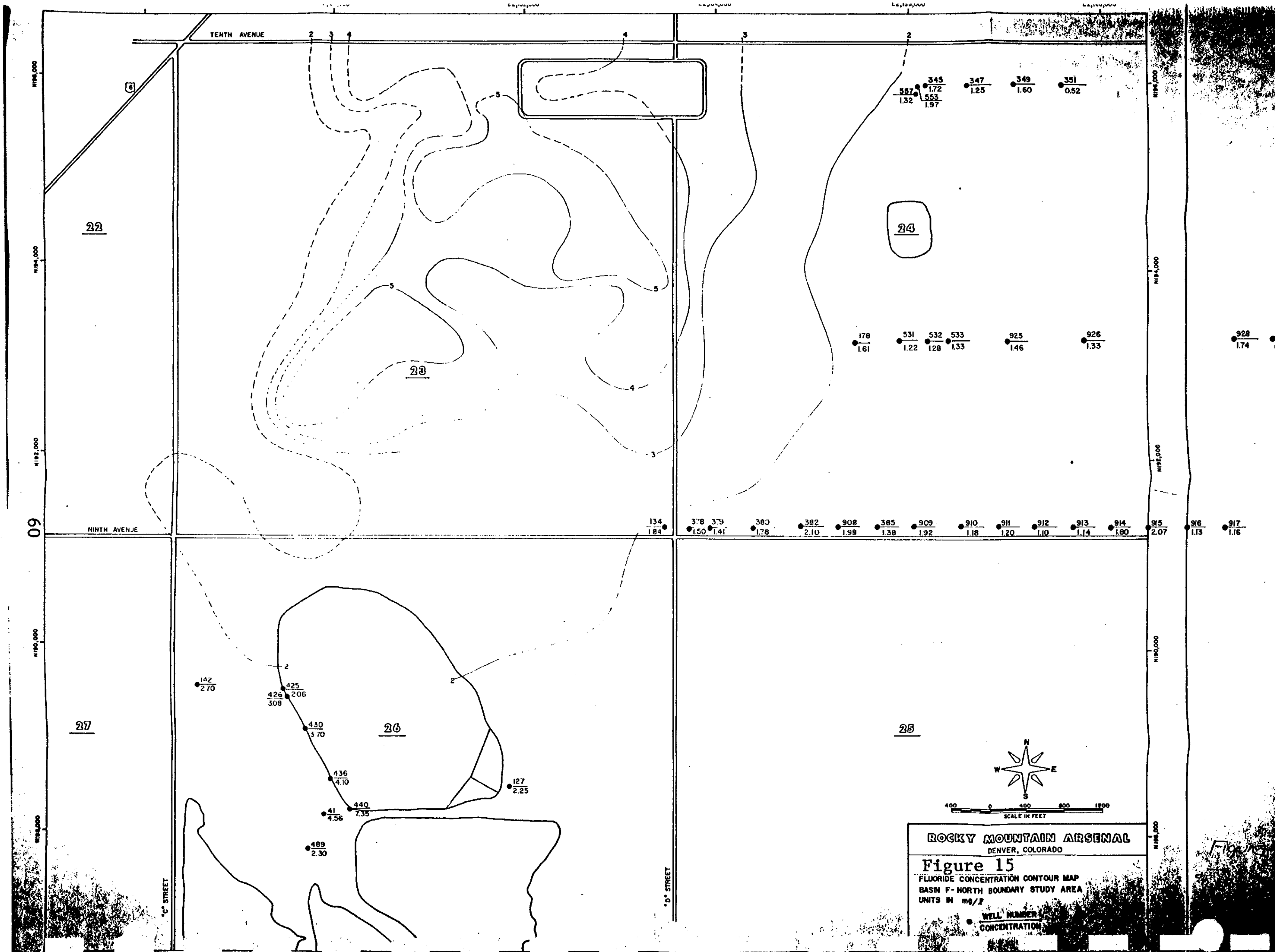


FIGURE 14 MEAN FLUORIDE CONCENTRATION (mg/l) AT NORTH BOUNDARY RMA (1977-1978)



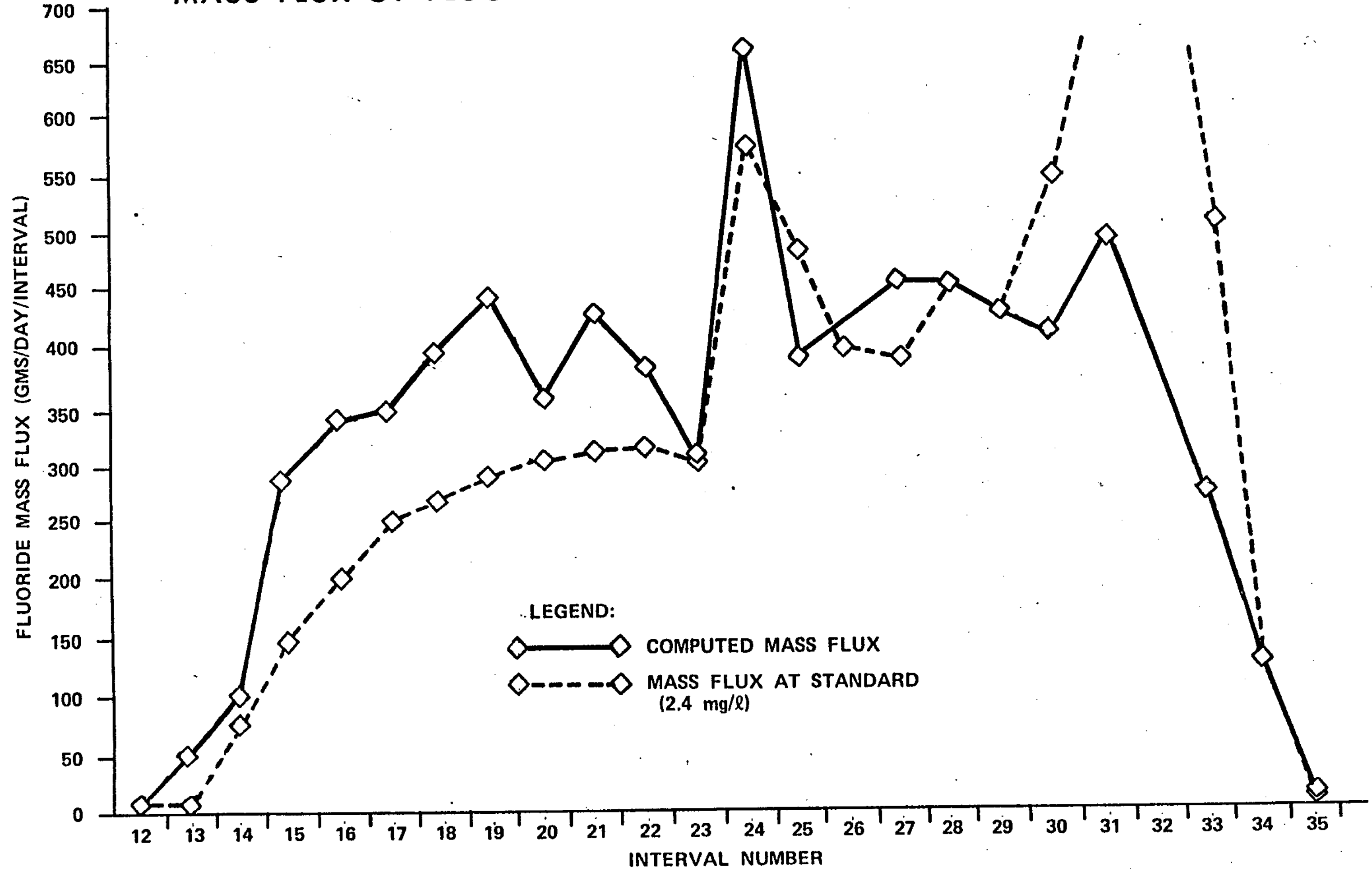
ROCKY MOUNTAIN ARSENAL
DENVER, COLORADO

Figure 15
FLUORIDE CONCENTRATION CONTOUR MAP
BASIN F- NORTH BOUNDARY STUDY AREA
UNITS IN mg/l

● WELL NUMBER / CONCENTRATION

FIGURE 16

MASS FLUX OF FLUORIDE ACROSS NORTH BOUNDARY OF RMA



BIBLIOGRAPHY

D'Appolonia, 1979, Report: Conceptual Design of the North Boundary Containment System, Rocky Mountain Arsenal, Denver, Colorado, Project No. RM79-480.

D'Appolonia, 1979, Report: Evaluation of North Boundary Pilot Containment System, Rocky Mountain Arsenal, Denver, Colorado, Project No. RM79-389.

Thompson, Douglas W. and Law, Paul K., 1979, Basin F to the North Boundary, Volume II: Groundwater Definition, Rocky Mountain Arsenal, Denver, Colorado, U.S. Army Corps of Engineers, Waterways Experiment Station.

Zebell, Robert A., 1979, Basin F to the North Boundary, Volume I: Geotechnical Definition, Rocky Mountain Arsenal, Denver, Colorado, U.S. Army Corps of Engineers, Waterways Experiment Station.

5.0 CONCLUSIONS

A. Groundwater flow at RMA is predominantly from south to north. Locally in the north boundary vicinity two separate subsurface water units make up the alluvial flow crossing the Arsenal's northern boundary. One of these units moves beneath Basin F in a northeasterly direction. Contaminants leached from surface waste basins move within this flow. The other groundwater unit is relatively free of contaminants as it proceeds parallel to First Creek. Therefore, water quality within the alluvial aquifer at the boundary is greatly dependent on the pathways taken by the individual groundwater units.

B. Total north boundary alluvial flow control is envisioned to meet applicable State of Colorado water quality guidelines. Interception of the entire alluvial aquifer will result in compositing both the contaminated and relatively noncontaminated groundwater flows units described above. Independent assessments have been completed for design purpose to predict expected flow and contaminant loading within the expanded north boundary control scheme.

C. Flow estimates of the alluvial aquifer at the north boundary are between 450 and 650 gpm. Variation of these estimates is due primarily to the choice of hydrodynamic parameters for the aquifer. Permeability estimates for the most permeable aquifer material range from 400 to 600 feet per day. Equal variation is noted in saturated thickness. These differences are within reason, however. Geohydrologic definition is not an exact science and is assumed adequate if an 80 percent accuracy is achieved.

D. Total mass of fluoride contained in the alluvial aquifer as it passes off RMA is estimated at 6.6 to 7.8 kg per day. This equates to an average fluoride water quality of 2.3 to 2.7 mg/ℓ. Because of the geohydrologic variation previously noted, refinement of these concentration expectations will not be possible until actual expanded system operation is accomplished.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX A

FINITE ELEMENT PROGRAM DESCRIPTION

TABLE OF CONTENTS

NOMENCLATURE

SYMBOL	DESCRIPTION	DIMENSION
a_{rk}	Coefficients in Equation (1.5.14))	
b	Thickness of aquifer	L
b'	Thickness of semipervious layer	L
D	Domain of interest	
e	Superscript representing an element	
E	Exponential integral	
i	Subscript	
I	Accretion	L/t
j	Subscript	
k	Subscript	
K_{xx}	Principal hydraulic conductivity along x axis	L/t
K_{yy}	Principal hydraulic conductivity along y axis	L/t
K'	Hydraulic conductivity of the semipervious layer	L/t
ℓ_1	Directional cosine with respect to x	
ℓ_2	Directional cosine with respect to y	
L	Length	L
m	An integer	
M	Number of nodes in one element	
MA	Order of approximation	
MAXBW	Upper bandwidth of matrix plus one	
n	Subscript	
N	Shape function	
NELS	Number of elements in whole grid system	
NNDS	Number of nodes in whole grid system	
N_n	Shape function for a specific point	
p	Pressure	M/Lt^2
P	Discharge per unit area	L^3/L^2t
P_w	Discharge per unit area at a specific point	L^3/L^2t
Q_2	Known flux along boundary	L/t

1.0 PROGRAM INFORMATION

1.1 ORIGIN AND PURPOSE OF PROGRAM

The computer program by the code name FICA (Flow in Confined Aquifer) was developed at Michigan State University, Department of Civil Engineering by Sirous Haji-Djafari and David C. Wiggert. This program is a modified and improved version of the already documented program by David C. Wiggert. This version uses isoparametric elements (quadrilateral, triangular or mixed elements) while the previous one only employed linear triangular elements. Some of the subroutines of the program are provided by Dr. L. J. Segerlind of the Department of Agricultural Engineering, Michigan State University.

The purpose of the program is to simulate the performance of an aquifer on a regional basis with a two-dimensional model. Finite element method is used to discretize the governing partial differential equations. By providing hydrodynamic parameters and stresses (such as transmissibility, storage coefficient, pumping rate, etc.), the program will find piezometric heads at the nodes and consequently the velocity vectors either at the nodes or within the elements. In addition, a steady-state solution can be computed either as an initial or final condition.

1.2 AREAS OF APPLICATION

The program FICA can be used to simulate two-dimensional groundwater flow in anisotropic and nonhomogeneous aquifers under confined or unconfined aquifers. Leaky artesian aquifers can be incorporated in the program. The other features of the program include time variable pumpage from well, natural or artificial recharge and line source recharge.

The Galerkin finite element formulation is employed to discretize the space and time derivatives of governing equations. Any isoparametric element can be used for grid system development.

1.3 PROBLEM DESCRIPTION AND USER ORIENTATION

The mathematical equations describing the flow through a confined or unconfined aquifer in two-dimensional horizontal planes are described in Section 1.4. Finite element formation of these equations are developed in Section 1.5. The computer model solves the flow equation in the following procedure.

- The domain of investigation is divided into a group of isoparametric elements. These elements can be triangular, quadrilateral or mixed elements of any kind (i.e., linear, quadratic or cubic). By means of these elements and employing the Galerkin-based finite element method, the mathematical equations are transformed to a system of first-order partial differential equations. The variation ϕ within the element depends on the kind of element. Other properties such as transmissibility, storage coefficient, and recharge are assumed constant within an element.

- To discretize the recurrence formula, different techniques are discussed (see Equation 1.5.14). The user has the option to choose any of the presented methods.

Some of the features of the program are as follow:

- At any designated node, time-variable pumping rates can be imposed.

- The system can be divided into regions and each region can have different known parameters such as transmissibility, recharge and storage coefficient.

- Initial piezometric head can be specified at all nodes or can be computed by the program.

- At any designated node, the value of the piezometric head can be specified (Dirichlet boundary condition).

- Along any designated element, line source can be incorporated.

- Piezometric heads can be computed either for a steady-state condition or for a transient state.

- Velocity vectors can be computed at any specified time either at the nodes or in the elements.

Basic assumptions used for developing this program are presented in Section 1.4.1. Among those, it is assumed that the variation of thickness of the aquifer is much smaller than the thickness itself. Furthermore, the vertical flow components are of minor importance and flow components are essentially two dimensional and horizontal.

When predicting drawdown close to the wells, true drawdown cannot be accurately computed at the well node. In order to obtain greater accuracy, the smaller nodes are used in the vicinity of the well point.

In the case of phreatic flow, it is important to note that the related equations are approximate only and their use may result in significant error if computed drawdown becomes large relative to the initial saturated thickness. The present program can be modified to permit the calculation of the apparent transmissibility defined by Equation 1.4.8. In this case, the average piezometric head is calculated at every time step and multipicked by hydraulic conductivity. If more accuracy is desired, it is possible to iterate within one time step, each iteration producing an update value for ϕ, which is used to reevaluate the apparent transmissibility. This procedure requires regenerating and decomposing global matrices when new transmissibilities are computed, and hence, increasing processing time.

Section 2.0 of this manual deals with usage information. To simplify input data preparation, two tables are presented. Table II-1 shows the name, location and order of variables along with the number of data cards and format numbers. The required format for each order is shown in Table II-2. A sample problem is given in more detail to orient the user with the steps which are required to use this program.

Section 3.0 contains the listing of the programs.

1.4 BASIC GOVERNING EQUATIONS OF GROUNDWATER FLOW

regional problems, two-dimensional horizontal flow is considered. The governing equations are well established (e.g., see Bear, 1972, and Pinder and Frind, 1972).

1.4.1 Basic Assumptions

The following assumptions are valid for regional groundwater flow:

(a) The flow is essentially horizontal in a two-dimensional plane (Figure I-1). This assumption is valid when the variation of thickness of the aquifer is much smaller than the thickness itself. This approximation fails in regions where the flow has a vertical component.

(b) The fluid is homogeneous and slightly compressible.

(c) The aquifer is elastic and generally non-homogeneous and anisotropic. The consolidating medium deforms during flow due to changes in effective stress with only vertical compressibility being considered.

(d) For the two-dimensional horizontal flow assumption, an average piezometric head is used where the average is taken along a vertical line extending from the bottom to the top of the aquifer, i.e.,

$$\phi_{av}(x,y,t) = \frac{1}{b}\int_{z=0}^{b} \phi(x,y,z,t)\,dz \qquad (1.4.1)$$

where b is the thickness of the aquifer.

The piezometric head is defined

$$\phi = \frac{p}{\gamma} + Z$$

where p is pressure, γ unit weight of fluid, and Z elevation from a datum.

1.4.2 Two-Dimensional Horizontal Flow - Confined Aquifer

The combined equation of motion and continuity for flow in a two-dimensional horizontal plane can be written

$$\frac{\partial}{\partial x}(K_{xx}b\frac{\partial \phi}{\partial x}) + \frac{\partial}{\partial y}(K_{yy}b\frac{\partial \phi}{\partial y}) - p + I = S_s b\frac{\partial \phi}{\partial t} \qquad (1.4.2)$$

where K_{xx}, K_{yy} are principal hydraulic conductivities along x and y direction, b is thickness of confined aquifer, p is the strength of a sink (or source), I is the vertical recharge or infiltration into the aquifer, S_s is the elastic specific storage, and $\frac{\partial}{\partial x}$; $\frac{\partial}{\partial y}$; $\frac{\partial}{\partial t}$ are partial derivatives with respect to x, y, and t, respectively. The product of hydraulic conductivity and the thickness of aquifer is called the transmissibility of the aquifer. Thus

$$T_{xx} = bK_{xx} \text{ and } T_{yy} = bK_{yy} \qquad (1.4.3)$$

and storage coefficient is defined by

$$S = S_s b \qquad (1.4.4)$$

For a confined aquifer, Equation (1.4.2) becomes

$$\frac{\partial}{\partial x}(T_{xx}\frac{\partial \phi}{\partial x}) + \frac{\partial}{\partial y}(T_{yy}\frac{\partial \phi}{\partial y}) - P + I = S\frac{\partial \phi}{\partial t} \qquad (1.4.5)$$

1.4.3 Initial and Boundary Conditions

Boundary Conditions

In order to solve a partial differential equation describing a physical phenomenon, it is necessary to choose certain additional conditions imposed by the physical situation at the boundaries (S) for the domain (D) under consideration. In general the equation for the boundary condition can be written

$$\beta_1(T_{xx}\frac{\partial\phi}{\partial x}\ell_1 + T_{yy}\frac{\partial\phi}{\partial y}\ell_2) + \beta_2\phi + \beta_3 = 0 \qquad (1.4.6)$$

where ℓ_1, ℓ_2 are the directional cosines, and β_1, β_2, and β_3 are given functions of position and possibly time. For flow through an aquifer, three different boundary conditions are applicable:

(a) Dirichlet or prescribed potential: In this case the potential is specified for all points along the boundary

$$\phi = -\frac{\beta_3}{\beta_2}; \qquad \beta_2 \neq 0$$

(b) Neumann or prescribed flux: Along a boundary of this type, the flux normal to the boundary surface is prescribed for all points of the boundary as a function of position and time

$$T_{xx}\frac{\partial\phi}{\partial x}\ell_1 + T_{yy}\frac{\partial\phi}{\partial y}\ell_2 = -\frac{\beta_3}{\beta_1} \text{ on } S; \quad \beta_1 \neq 0$$

A special case of the Neumann condition is the impervious boundary where the flux vanishes everywhere on the boundary, i.e.,

$$\beta_3 = 0$$

(c) Cauchy boundary: This problem occurs when the potential and its normal derivative are prescribed on the boundary in the combined form, and the entire Equation (1.4.6) is used.

Different forms of Equation (1.4.6) for three types of boundary conditions are summarized in Table I-1. In general, for a flow problem one will have mixed boundary conditions in which the Dirichlet condition will apply over a part of the boundary and the Neumann condition will be specified for the remaining portion (Bear, 1972).

Initial Conditions

At the initial time, either the piezometric heads are known in the entire domain (D) or the hydrologic stresses (such as pumping and recharge) are specified and boundary conditions are known. For the second case the system has reached the steady state, so the solution of the equation

$$\frac{\partial}{\partial x}(T_{xx}\frac{\partial \phi}{\partial x}) + \frac{\partial}{\partial y}(T_{yy}\frac{\partial \phi}{\partial y}) - P + I = 0 \qquad (1.4.7)$$

will yield piezometric heads for the initial time.

1.4.4 Two-Dimensional Horizontal Flow - Unconfined Aquifer

The aquifer shown in Figure I-2 is for saturated flow bounded above by a phreatic surface. For regional analysis it is possible to describe the flow with a relation analogous to Equation (1.4.2) by making use of the Dupuit approximation. In this case the transmissibility becomes

$$T_{xx} = \phi K_{xx}$$
$$\qquad (1.4.8)$$
$$T_{yy} = \phi K_{yy}$$

where it is assumed the impervious boundary is the datum. In Equation (1.4.8), ϕ is the piezometric head at any specified location. When applying a mass balance to a control volume in Figure I-2, in addition to compressibility of the fluid and porous media, the variation of available storage due to vertical movement of the phreatic surface should be considered. The concept of drainable water or equivalently specific yield, S_y, can be used to describe this phenomenon. Since in most cases $S_y >> S$, in Equation (1.4.2) S_y can be substituted for S.

Equation (1.4.2) takes the form of

$$\frac{\partial}{\partial x}(K_{xx}\phi\frac{\partial \phi}{\partial x}) + \frac{\partial}{\partial y}(K_{yy}\phi\frac{\partial \phi}{\partial y}) - P + I = S_y \frac{\partial \phi}{\partial t} \qquad (1.4.9)$$

A fundamental difference occurs, however, due to the dependence of transmissivity upon ϕ as shown in Equation (1.4.8). Thus the unconfined flow equation is nonlinear, and numerically is treated in a quasi-linear fashion. In unconfined conditions, infiltration, I, directly enters the saturated zone. Infiltration can be either natural or artificial input to the system.

1.4.5 Infiltration

Unconfined aquifer recharge, I, directly infiltrates to the aquifer. In nonleaky-confined aquifers, the recharge value is zero. In semiconfined (leaky) aquifer (see Figure I-3), the vertical leakage is calculated (Bear, 1972) by the Equation

$$I = \frac{\phi_o - \phi}{\sigma'} \qquad (1.4.10)$$

where:

ϕ_o = potential head in the aquifer above the semipervious layer

ϕ = piezometric head in confined aquifer

σ' = the resistance of the semipervious layer and is equal to b'/k'

b' = thickness of semipervious layer

K' = hydraulic conductivity of the semipervious layer

1.4.6 Velocity Vectors

The equation of apparent velocity (flow per unit area) along x- and y-directions can be written as follows:

$$V_x = -K_{xx} \frac{\partial \phi}{\partial x} \qquad (1.4.11a)$$

$$V_y = -K_{yy} \frac{\partial \phi}{\partial y} \qquad (1.4.11b)$$

where

V_x = velocity vector along x-direction

V_y = velocity vector along y-direction.

The other terms are defined previously.

The magnitude and direction of the velocity vectors (Figure I-4) at any given location and time can be obtained by

$$V = \sqrt{V_x^2 + V_y^2} \qquad (1.4.12)$$

$$\alpha = \arctan\left(V_y / V_x\right) \qquad (1.4.13)$$

where

V = magnitude of the velocity always positive

α = direction of the velocity measured from positive x.

1.5 METHOD OF COMPUTATION

The finite element method is a numerical technique which is used to approximate a continuous partial differential equation in a given domain D with specified boundary conditions along boundaries S. The key features of the finite element concept are (Norrie and de Vries, 1973):

1. The domain is divided into subdomains or finite elements, usually of the same order.

2. The trial solution is prescribed (functionally) over the domain in a piecewise fashion, element by element.

A detailed formulation of the finite element method is given by Zienkiewicz (1971), Norrie and de Vries (1973). This technique has been utilized by several investigators (Javandel and Witherspoon, 1971; Pinder and Frind, 1972; Neuman and Witherspoon, 1971; Desai, 1972; Cheng and Li, 1973; and France, 1971, 1974) to solve transient flow problems in a confined or unconfined aquifer.

In this section a brief discussion of the Galerkin based finite element technique is given and the method is used to discretize the space derivatives of the flow equation. The simultaneous solution of velocity

vectors is also described, i.e., the Galerkin formulation of the Darcy law is constructed and velocity components are calculated at the nodes.

1.5.1 The Galerkin Finite Element Method

In the finite element technique the domain D is divided into subdomains D^e which are called elements. Each element is designated by nodes. In this documentation NELS represents the number of elements, M is the number of nodes in each element, and NNDS stands for the total number of nodes in domain D (see Figure I-7).

Consider a problem of solving approximately a set of differential equations in which the unknown function $\{\phi\}$ has to be satisfied in the domain D with the boundary conditions specified along S. The governing equation can be written

$$f(\{\phi\}) = 0$$

Let the trial solution for this equation be $\hat{\phi}$

$$\hat{\phi} = [N]\{\phi\} = \sum_{n=1}^{M} N_n \phi_n \tag{1.5.1}$$

where $[N] = [N(x,y)]$ are shape functions (prescribed functions of coordinates) and $\{\phi\} = \{\phi(t)\}$ is a set of M unknown parameters. In general, the equation of residual (or error) is formed in the following way:

$$R = f_{D^e}(\{\phi\}) - f_{D^e}(\{\hat{\phi}\}) = -f_{D^e}(\{\hat{\phi}\}) \neq 0 \tag{1.5.2}$$

The best solution will be one in which the residual R has the least value at all points in the domain D^e. An obvious way to achieve this (Zienkiewicz, 1971) is to make use of the fact that if R is identically zero elsewhere, then

$$\int_{D^e} W\, R\, dD = 0 \tag{1.5.3}$$

where W is any function of the coordinates. If the number of unknown parameters $\{\phi\}$ is NNDS and NELS linearly independent functions W_k are chosen, one can write a suitable number of simultaneous equations as

$$\int_{D^e} W_k\, R\, dD = \int_{D^e} W_k f([N]\{\phi\})dD = \{0\} \qquad k = 1, \ldots, M \tag{1.5.4}$$

where W_k is called the weighting function. If the shape function N_k is to be chosen as the weighting function, the process is termed the Galerkin procedure which is used henceforth. The element equations can be assembled by

$$\sum_{e=1}^{NELS} \left(\int_{D^e} W\, R\, dD \right) = 0 \tag{1.5.5}$$

to yield the global relations for domain D.

1.5.2 <u>Finite Element Formulation of Flow Equation</u>

The residual equation for flow in a confined horizontal aquifer (Equation 1.4.5) with no vertical recharge can be written as

$$R = S\frac{\partial\hat{\phi}}{\partial t} + P - \left(\frac{\partial}{\partial x}(T_{xx}\frac{\partial\hat{\phi}}{\partial x}) + \frac{\partial}{\partial y}(T_{yy}\frac{\partial\hat{\phi}}{\partial y}) \right) \tag{1.5.6}$$

The symbol ^ represents the numerical approximation of ϕ. Substituting Equation (1.5.6) into Equation (1.5.4), one obtains

$$\int_{D^e} \left[S\frac{\partial\hat{\phi}}{\partial t} + P - \left\{ \frac{\partial}{\partial x}\left(T_{xx}\frac{\partial\hat{\phi}}{\partial x} \right) + \frac{\partial}{\partial y}\left(T_{yy}\frac{\partial\hat{\phi}}{\partial y} \right) \right\} \right] N_k\, dD = 0 \qquad k=1,\ldots M \tag{1.5.7}$$

By use of the Green theorem, the third term can be modified

$$\int_{D^e} \left(\frac{\partial}{\partial x} T_{xx}\frac{\partial\hat{\phi}}{\partial x} + \frac{\partial}{\partial y} T_{yy}\frac{\partial\hat{\phi}}{\partial y} \right) N_k dD = -\int_{D^e} \left(T_{xx}\frac{\partial N_k}{\partial x}\frac{\partial\hat{\phi}}{\partial x} + T_{yy}\frac{\partial N_k}{\partial y}\frac{\partial\hat{\phi}}{\partial y} \right) dD + \int_{S^e} N_k \left(T_{xx}\frac{\partial\hat{\phi}}{\partial x}\ell_1 + T_{yy}\frac{\partial\hat{\phi}}{\partial y}\ell_2 \right) dS \tag{1.5.8}$$

The last term in Equation (1.5.8) is nonzero only for elements which contain the Neumann flux boundary condition

$$-\int_{S^e} N_k \left(T_{xx} \frac{\partial \hat{\phi}}{\partial x} \ell_1 + T_{yy} \frac{\partial \hat{\phi}}{\partial y} \ell_2 \right) dS = \int_{S^e} N_k Q_2 \, dS \qquad (1.5.9)$$

where Q_2 is known flux along the boundary. Substituting Equation (1.5.8) and Equation (1.5.1) into Equation (1.5.7) and rearranging the terms, one obtains

$$\int_{D^e} \phi_n \left(T_{xx} \frac{\partial N_k}{\partial x} \frac{\partial N_n}{\partial x} + T_{yy} \frac{\partial N_k}{\partial y} \frac{\partial N_n}{\partial y} \right) dD + \qquad (1.5.10)$$

$$\int_{D^e} S \, N_k N_n \frac{\partial \phi}{\partial t} dD + \int_{D^e} N_k P \, dD + \int_{S^e} N_k Q_2 \, dS = 0$$

Since ϕ_n and its time derivatives are independent of the coordinates, they can be taken out of the integrals. Equation (1.5.10) can be written in matrix form

$$[B]^e \{\phi\}^e + [H]^e \frac{\partial}{\partial t} \{\phi\}^e = \{F\}^e \qquad (1.5.11)$$

where

$$[B]^e = B^e_{kn} = \int_{D^e} \left[T_{xx} \frac{\partial N_k}{\partial x} \frac{\partial N_n}{\partial y} + T_{yy} \frac{\partial N_k}{\partial y} \frac{\partial N_n}{\partial y} \right] dD \qquad (1.5.12a)$$

$k,n=1,\ldots M$

$$[H]^e = H^e_{kn} = \int_{D^e} S \, N_k \, N_n \, dD \qquad (1.5.12b)$$

$i,j=1,2$

$$\{F\}^e = F^e_k = -\int_{S^e} N_k Q_2 \, dS - \int_{D^e} P \, N_k \, dD \qquad (1.5.12c)$$

It is assumed that the storage coefficient is constant throughout the element and that the element coordinate axes coincide with the principal direction of the transmissivity tensor: the transmissivity can be defined either at the nodes or at each element. Evaluation of Equation (1.5.12) for different types of elements is discussed by Zienkiewicz (1971) and is presented in more detail by Haji-Djafari (1976). Upon evaluation of Equation (1.5.12) for all elements and transformation to a global coordinate system, they are assembled by virtue of Equation (1.5.5) into a global relationship

$$[B]\ \{\phi\} + [H]\ \{\frac{\partial\phi}{\partial t}\} = \{F\} \tag{1.5.13}$$

The parameter $\{\phi\}$, matrices [B] and [H], and force vector {F} are the summation of the corresponding terms in Equation (1.5.12) over all the elements in the Domain D. The matrices [B] and [H] are banded symmetric. Equation (1.5.13) is a set of first order linear differential equations with unknowns $\{\phi\}$ and can be solved simultaneously at the given nodes in the space domain.

The recurrence formula for Equation (1.5.13) has the form (Haji-Djafari, 1976)

$$\left(a_{11}\ [B] + \frac{a_{12}}{\Delta t}\ [H]\right)\ \{\phi(t+\Delta t)\} = \left(a_{21}\ [B] + \frac{a_{22}}{\Delta t}\ [H]\right)$$

$$\{\phi(t)\} + a_{13}\ \{F(t+\Delta t)\} + a_{23}\ \{F(t)\} + \tag{1.5.14}$$

In Equation (1.5.14), Δt is time step and a's are coefficients which their value are given Section 2.2-Order 12.

1.5.3 Finite Element Computation of Velocity Vectors

Mathematical equations of velocity vectors are presented in Section 1.4.6. Once the piezometric heads have been determined, velocity vectors (or

flow per unit area) can be evaluated. Two techniques are employed to compute the velocity vectors by finite element method.

The first technique which is called "direct method," piezometric head is approximated by Equation 1.5.1. The resulting equations will be:

$$\left.\begin{aligned} V_x &= -K_{xx} \frac{\partial N_n}{\partial x} \phi_n \\ V_y &= -K_{yy} \frac{\partial N_n}{\partial y} \phi_n \end{aligned}\right\} \quad n = 1, \ldots M, \text{ number of nodes in an element} \tag{1.5.15}$$

In Equation (1.5.15) ϕ_n's are piezometric heads at the nodes, and are known. The terms $\frac{\partial N_n}{\partial x}$ and $\frac{\partial N_n}{\partial y}$ are first derivatives of shape functions and are evaluated at the point of interest, usually at the center of element.

In the second technique which is termed "simultaneous method," the Galerkin-based finite element formulation of Equation (1.4.11) is developed. This procedure yields a set of equations which are solved simultaneously to find the velocity vectors at the nodes.

The detailed procedure is given by Haji-Djafari, 1976 and the results are summarized below.

The element equations for x-component of velocity vector have the form:

$$[H]^e \left\{V_x^c\right\}^e = \left\{F_x\right\}^e \tag{1.5.16}$$

where

$$[H]^e = \int_{D^e} N_k N_n \, dD \qquad K, n = 1, 2, \ldots M \tag{1.5.17}$$

$$\left\{F_x\right\}^e = -K_{xx} \int_{D^e} N_k \frac{\partial N_n}{\partial x} \phi_n \, dD \qquad K, n = 1, 2, \ldots M \tag{1.5.18}$$

Constructing a global matrix yields

$$[H] \left\{ V_x^c \right\} = \left\{ F_x \right\} \tag{1.5.19}$$

In Equation (1.5.19), [H] is banded symmetric matrix, and $\{F_x\}$ is known column force. The solution of Equation (1.5.19) yields the x-component of velocity at each node simultaneously.

Similarly, the finite element equations of the velocity vector along y-direction have the forms similar to Equation (1.5.16) through Equation (1.5.19), except subscript x is replaced by y.

1.6 ACCURACY, LIMITATIONS AND RESTRICTIONS

As presented in Chapter 2.0, the solutions obtained from this program are compared with the exact solution by Theis and good agreement is found. However, this program is a numerical model which is developed using finite element method. As with any other numerical technique, there are errors which are associated with size and kind of elements; numerical integration method, and discretization of the recurrence formula; size of time step; etc. Experience shows the accuracy of the results will improve by reducing the size of elements and time step. In general, the program has been verified and the accuracy of the results are within an acceptable range.

Limitations and restrictions of the program are described in appropriate sections, the major ones being as follows:

- Simulation of the aquifer performance is limited to regional situations as long as the validity of basic assumptions described in Section 1.4.1 are maintained.
- Although any kind of elements can be used, their improper combination is restricted as described in Section 2.2.
- Units of the input parameters should be consistent.

1.7 PROGRAM ORGANIZATION

The program consists of main program FICA and 15 internal subroutines. Main program functions as an organizator; it reads job specification parameters; sets the dimensions of the variables; calls for input subroutine; initializes and increments time; calls for subroutines such as those identifies matrix bandwidth, constructs global matrices, constructs force vector, solves the piezometric heads, prints the piezometric heads, calculates the discharge vectors; and finally, the main program terminates the job if there are no new data set for computation. The flow chart for the main program is given in Figure I-5.

The function of each subroutine is described in the computer program (see Section 3.0 for program listing).

1.8 CASE STUDIES

1.8.1 Regional Aquifer System

The domain illustrated in Figure I-6 is a confined aquifer approximately 18,000 m in length and 5000 m wide. A well field is located at E, which pumps 18,930 m^3/d from the system. Aquifer properties are K = 50 m/d, S = 0.001, and two thicknesses of 10 and 20 m, resulting in two transmissibility zones of 500 and 1000 m^2/d, respectively. No flow boundaries exist along AB and CD, and known potential conditions are assigned along AD and BC. The system is divided into isoparametric linear elements yielding 117 nodes and 104 elements (Figure I-7). The predicted drawdown at two locations at points G and F for 40 days after pumping is shown in Figure I-8.

The same aquifer is simulated using the method of characteristics (Wiggert & Wylie, 1976). The results obtained from the finite element method are used to justify the capability of the method of characteristics. Good agreement is found between the results of these two models, as well as an analytical solution, as shown in Figure I-8.

1.8.2 Single Horizontal Drain

The second case study involves the simulation of flow movement to a single horizontal drain 18.3 m in length. At the initial time, the water level is assumed to be 24.4 m above the barrier boundary. Water is allowed to discharge from only seven points along the drain, as shown in Figure I-9. Known potential conditions are assigned along AB.

The system is divided into isoparametric elements yielding 181 nodes and 147 elements. The properties of the porous medium are K = 0.05 m/day and effective porosity = 0.2. Flow vectors for steady state conditions are depicted in Figure I-9.

The length of arrows represents the relative magnitude of the velocities It is interesting to note that most of the water is drained in the portion close to the constant head zone. Only a small quantity of water is reaching to the far end of the pipe.

LIST OF REFERENCES

Bear, J., 1972, Dynamics of Fluids in Porous Media, American Elsevier Publishing Company, Inc., New York.

Carahan, B., H. A. Luther and J. O. Wilkes, 1969, Applied Numerical Methods, John Wiley and Sons, Inc., New York.

Cheng, R. T. and C. Y. Li, 1973, On the Solution of Transient Free Surface Flow Problems in Porous Media by Finite Element Method, J. of Hydrology, 20, pp. 49-63.

Davis, S. N. and R. J. M. DeWiest, 1966, Hydrogeology, John Wiley and Sons, New York.

Desai, C. S., 1972, Seepage Analysis of Earth Bank Under Draw-down, J. of the Soil Mechanics and Foundation Division ASCE, 98(SM11), pp. 1143-1162.

Desai, C. S. and J. F. Abel, 1972, Introduction to the Finite Element Method, Van Nostrand Reinhold Company, New York.

Ergatoudis, I., B. M. Irons and O. C. Zienkiewicz, 1968, Curved isoparametric quadrilateral elements for finite element analysis, International J. Solids Structures, 4, pp. 31-42.

France, P. W., 1971, Finite Element Analysis of Unconfined Seepage Problems, Ph.D. thesis, University of Wales, Swansea Glamorgan, England.

France, P. W., C. J. Parekh, J. C. Peters and C. Taylor, 1971, Numerical Analysis of Free Surface Seepage Problems, J. of the Irrigation and Drainage Division ASCE, 97(IR1), pp. 165-179.

France, P. W., 1974, Finite Element Analysis of Three-Dimensional Groundwater Flow Problems, J. of Hydrology, 21, pp. 381-398.

Haji-Djafari, S., 1976, Two-Dimensional Finite Element Analysis of Transient Flow and Tracer Movement in Confined and Phreatic Aquifers, Ph.D. thesis, Michigan State University, East Lansing.

Javandel, I. and P. A. Witherspoon, 1969, A Method of Analyzing Transient Fluid Flow in Multilayered Aquifer, Water Resources Research, 5(4), pp. 856-869.

Neuman, S. P. and P. A. Witherspoon, 1970, Finite Element Method of Analyzing Steady Seepage with a Free Surface, Water Resources Research, 6(3), pp. 889-897.

Neuman, S. P. and P. A. Witherspoon, 1971, Analysis of Nonsteady Flow with a Free Surface Using the Finite Element Method, Water Resources Research, 7(5), pp. 611-623.

Norrie, D. H. and G. deVries, 1973, The Finite Element Method, Academic Press, New York.

Pinder, G. F. and E. O. Frind, 1972, Application of Galerkin's Procedure to Aquifer Analysis, Water Resources Research, 8(1), pp. 108-120.

Wiggert, D. C. and E. B. Wylie, 1976, Numerical Predictions of Two-Dimensional Transient Groundwater Flow by the Method of Characteristics, Water Resources Research, 12(5), pp. 971-977.

Zienkiewicz, O. C., 1971, The Finite Element Method in Engineering Science, McGraw-Hill Publishing Company, London.

APPENDIX B

INTERIM MASS FLUX USER'S MANUAL

by

H.O. Eberhart

POTOMAC RESEARCH, INCORPORATED
Alexandria, Virginia 22311

January 1979

Prepared For:

Department of the Army
Chemical Systems Laboratory
Developmental Support Division
Scientific & Engineering Applications Branch

Task: 05

Contract Number: DAAK11-77-C-0112
Installation Restoration Data Base Management

9.4 INTERIM MASS FLUX PROGRAM

9.4.1 ABSTRACT:

This FORTRAN program will plot a bar or line graph of mass flux on the Tektronix 4051 screen or the 4662 plotter for user-provided input parameters: contaminant information, transect definition, geohydrologic information, and output specifications.

The mass flux is computed from the formula

$$\emptyset = KLtI \times C \times U$$

where
$\emptyset$ = mass flux across the transect in gms/day
K = permeability of saturated zone in feet/day
L = saturated length in feet
t = saturated flow thickness in feet
I = gradient of the water table
C = contaminant concentration in mg/liter or μg/liter
U = units' adjustment

The above formula is essentially Darcy's law for the flow of ground water.

This program is an interim version of the mass flux calculation. Only the sampling and analysis chemical file is used as input for programmatic search. All geohydrologic information is furnished by the user.

9.4.2 PROCEDURE

This section has been written for the person who is not familiar with a digital computer but is motivated to use the computer as a tool in his or her daily job. An example will be explained step by step to enable the user to gain sufficient knowledge and confidence in the use of this program.

Before reading further it is necessary that the user understand how to log on the Univac 1108 computer as described in sections 1.1 through 1.3 of the IR Data Management User's Guide.

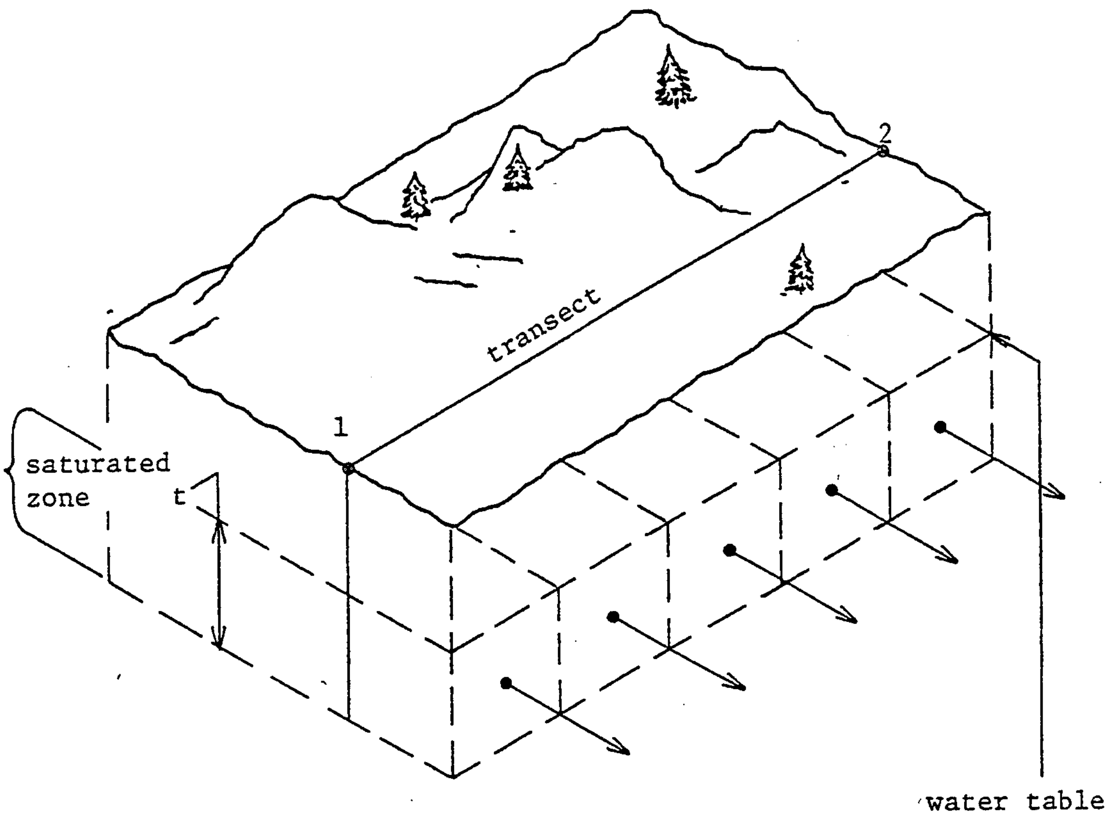
Ensure that the 4631 hard copy unit and the 4662 plotter are turned on and the four binary switches on the plotter are set to "32A3."

The bold type below will indicate the computer's response. The prompting symbol **<** means that the user is expected to furnish input to the program from the keyboard.

Example: User wishes to plot the mass flux of contaminant DBCP during 1978 across a transect starting at Well 23001 and continuing 4000 feet east. User determines that there should be eight intervals along the transect and that he does not want a standard concentration graph.

The user should study Figure 4.1 on the next page in order to see a graphic representation of the mass flux formula.

3-Dimensional View:



Plan View:

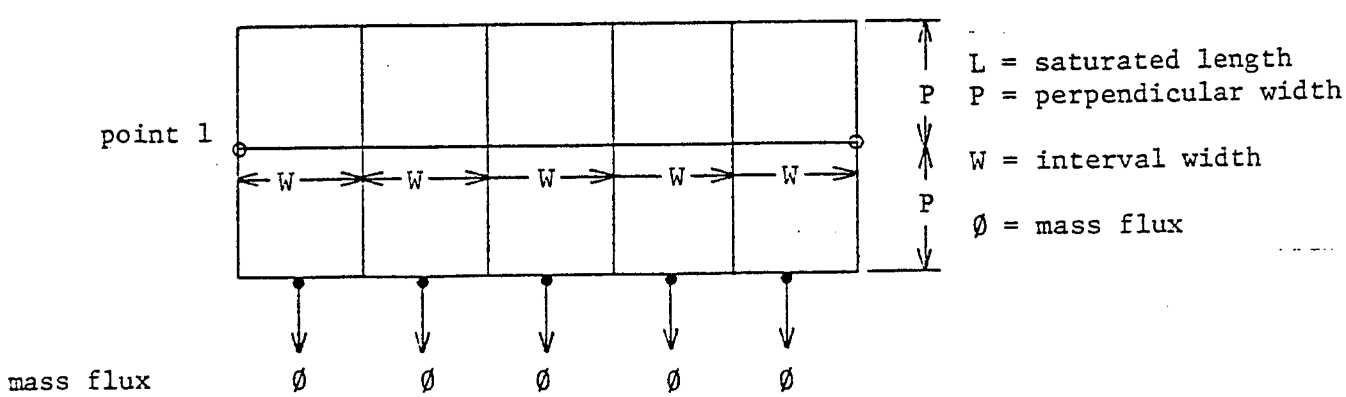


Figure 4.1 - Flow of contaminant through the saturated zone

Type @ADD IR*GEOLPRO.MF and press [RETURN] in order to start the program. The computer will respond with:

```
END ERS.
READY
READY
READY
READY
MAP 29R1 SL73R1 05/08/79 08:26:18
```

The computer will print the program title and first question:

```
MASS FLUX

* RUN PARAMETERS *                19 JAN 79

* * * * * * * BASIC INPUT
ENTER INSTALLATION CODE  (2 LETTERS)
>
```

Acceptable responses: RM - Rocky Mountain Arsenal

Type "RM" and press [RETURN].

The computer will print the second question:

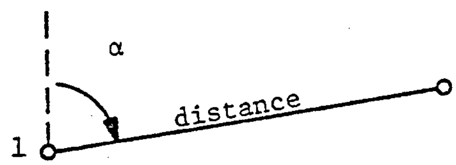
```
DO YOU WANT TO SPECIFY THE TRANSECT BY
      POINT, DISTANCE, ANGLE   (1)
      OR   2 POINTS            (2)?

      ENTER 1 OR 2

>
```

There are two methods of specifying the transect:

- point 1, distance from 1 at bearing angle α from grid north



- point 1 and point 2

Either method allows the point to be entered as site type and site ID or in state planar coordinates.

For the example, type "1" and press [RETURN].
The computer responds:

```
FOR POINT 1,  DO YOU WANT TO USE
      SITE TYPE + SITE ID     (1)
      OR   COORDINATES        (2)?

      ENTER 1 OR 2

>
```

Type "1" and press [RETURN].

The computer will next ask for site type and site ID.

```
ENTER SITE TYPE   (4 LETTERS;
        EXAMPLES:  BORE, WELL)

>
```

Acceptable responses: BORE
WELL

Type "WELL" and press [RETURN].

The computer responds:

```
ENTER SITE ID      (1 TO 10 LETTERS
        OR DIGITS; EXAMPLE  01001)
>
```

Type "23ØØ1" and press [RETURN].

The next two questions that the computer will ask concern distance and bearing angle.

```
ENTER DISTANCE FROM POINT 1   IN FEET
        (1 TO 5 DIGITS + DECIMAL POINT;
        EXAMPLE:  5280.)
>
```

Acceptable response: number with decimal point
Type "4ØØØ." and press [RETURN].
The computer responds:

```
ENTER BEARING ANGLE FROM POINT 1   IN DEGREES
            CLOCKWISE FROM NORTH; 0. = GRID NORTH
            (1 TO 3 DIGITS + DECIMAL POINT;  EXAMPLE:  90.)

>
```

Acceptable response: number with decimal point.

Type "90." and press [RETURN].

```
ENTER INTERVAL WIDTH ALONG THE TRANSECT  IN FEET
        (1 TO 5 DIGITS + DECIMAL POINT;
        EXAMPLE:  200.)

>
```

Acceptable response: number with decimal point.

This number is W in Figure 4.1. Type "500." and press [RETURN].

Next the computer will ask:

```
ENTER PERPENDICULAR DISTANCE FROM THE TRANSECT  IN FEET
        (1 TO 4 DIGITS + DECIMAL POINT;
        EXAMPLE:  200.)
>
```

Acceptable response: number with decimal point.

This number is P in Figure 4.1. Type "1000." and press [RETURN]. Note that at this point user has built a box of length 4000 feet and width 2000 feet comprised of 8 smaller boxes as shown below in Figure 4.2

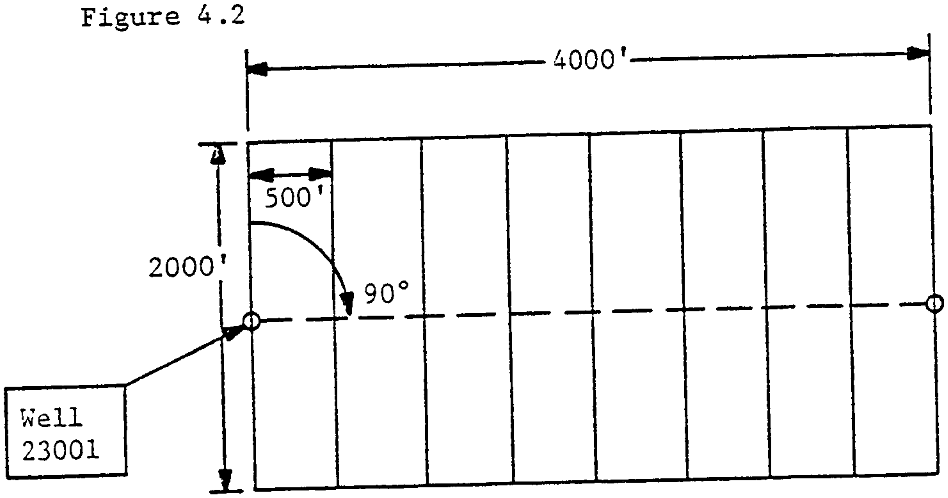


Figure 4.2 - Sample box generated by user

The computer will compute the number of intervals along the transect:

```
YOU HAVE     8 INTERVALS.
DO YOU WANT TO SPECIFY A NEW INTERVAL WIDTH?  (Y OR N)
>
```

Type "N" and press [RETURN].

The next group of questions concern contaminant input:

```
* * * * * * * CONTAMINANT INPUT
DO YOU WANT TO SPECIFY A CHEMICAL
      TO GET A COMPUTED GRAPH?  (Y OR N)
>Y
```

Type "Y" and press [RETURN].

The computer responds:

```
ENTER CHEMICAL TEST NAME  (1 TO 6 LETTERS
      OR DIGITS; EXAMPLE  DBCP)
>
```

Acceptable response: chemical test name
This contaminant is taken from section 2.1 of the IR Data Management User's Guide. Type "DBCP" and press [RETURN].

```
ENTER SITE TYPE FOR THE SAMPLING  (4 LETTERS;
      EXAMPLES:  BORE, WELL)
>
```

Acceptable responses: BORE
WELL

Type "WELL" and press [RETURN].

The computer will ask for the date range:

```
ENTER BEGINNING JULIAN DATE  (0 FOR EARLIEST
         OR  5 DIGITS; EXAMPLE:  78244)
>
```

Acceptable response: YYDDD or Ø

where YY = two-digit year
DDD = day of the year
Ø = earliest date on file

Type "78001" and press [RETURN].
The computer responds:

```
ENTER ENDING JULIAN DATE     (0 FOR LATEST
         OR  5 DIGITS; EXAMPLE:  78244)
>
```

Acceptable response: YYDDD or Ø

where YY = two-digit year
DDD = day of the year
Ø = latest date on the file

Type "78365" and press [RETURN].

Next the computer will ask how to deal with multiple samples for one site type + site ID that arise during the search procedure:

```
WHERE MULTIPLE SAMPLES EXIST AT THE SITE TYPE+ID
      AND WITHIN THE DATE RANGE CHOSEN,
      DO YOU WANT HIGHEST, LATEST, OR MEAN?  (H, L, OR  M)

      NOTE:  USE OF MEAN VALUES OVER LONG INTERVALS
             OF TIME OR DEPTH WILL MASK TRENDS; THEREFORE,
             PROCEED WITH CAUTION.
>
```

Acceptable responses:

H - Highest sample value at the location for the date range specified

L - Latest (most recent) sample value at that location

M - Mean or weighted average of sample values at that location

Type "H" and press [RETURN].

At this point the user can specify a second curve to be plotted; i.e., the standard concentration curve on the same set of x- and y-axes, which can be useful in comparing high and low values of mass flux. To specify standard concentration, user will have to enter chemical test name, units, and value.

```
DO YOU WANT TO SPECIFY A CHEMICAL
        TO GET A STANDARD GRAPH?  <Y OR N>
>
```

The user does not want a standard graph, so type "N" and press [RETURN].

The next group of questions concerns geohydrologic input:

```
* * * * * * * GEOHYDROLOGIC INPUT

* * * * * * * FOR INTERVAL  1

ENTER PERMEABILITY  IN FEET/DAY
        (1 TO 4 DIGITS + DECIMAL POINT;
        EXAMPLE:  4.44)
>
```

Acceptable response: number with decimal point
Type "100." and press [RETURN].

```
ENTER WATER TABLE GRADIENT
        (DECIMAL POINT + 1 TO 6 DIGITS;  EXAMPLE:  .000155)

>
```

Acceptable response: decimal point and number
Type ".01" and press [RETURN].

```
ENTER SATURATED THICKNESS  IN FEET
        (1 TO 3 DIGITS + DECIMAL POINT;  EXAMPLE:  90.)
>
```

Acceptable response: number with a decimal point
Type "10." and press [RETURN].

```
ENTER SATURATED LENGTH     IN FEET
        (1 TO 5 DIGITS + DECIMAL POINT;
        EXAMPLE:  5280.)
>
```

Acceptable response: number with decimal point
This number does not have to equal interval width W.
Type "500." and press [RETURN].

The preceding four questions will be repeated for each interval until the user has entered all geohydrologic information.

Next the computer responds:

```
* * * * * * * OUTPUT SPECIFICATIONS

DO YOU WANT YOUR OUTPUT TO BE A BAR GRAPH
      OR A LINE GRAPH?       (B OR L)
>
```

Acceptable responses:

B - Bar graph for each

L - Line graph for each

Type "L" and press [RETURN].

Next, a table of input parameters will be printed:

```
* RUN PARAMETERS *                  4 MAY 79

   INS: RM
              CONTAM 1: DBCP      78001-78365     H

   INTERV WIDTH:     500.  PERPENDICULAR:     1000.

   TRANSECT LENGTH:         4000.  AT  90. DEG

   INTERV       PERM     GRAD    THICK   LENGTH
      1        100.0    .0100    10.0   ******
      2        100.0    .0100    10.0     500.
```

Assume an error has been made at the value indicated by asterisks.

```
    DO YOU WANT TO CORRECT ANY GEOHYDROLOGIC VALUES?  (Y OR N)
>
```

Type "Y" and press [RETURN].

```
    ENTER INTERVAL NUMBER
          (2 DIGITS INCLUDING LEADING ZERO; EXAMPLE:  03)
>
```

Type "01" and press return.
Note the leading zero.

```
ENTER COLUMN NUMBER
        (1 DIGIT; 1=PERM,2=GRAD,3=THICK,4=LENGTH)
>
```

Type "4" and press [RETURN].

```
ENTER CORRECTED VALUE
        (1 TO 7 DIGITS + DECIMAL POINT)
>
```

Now the user should enter the new value; type "500." and press [RETURN].

```
DO YOU WANT TO CORRECT ANY GEOHYDROLOGIC VALUES?  (Y OR N)
>
```

Type "N" and press [RETURN]. The new table of input parameters will be printed.

```
* RUN PARAMETERS *                    8 MAY 79

    INS: Rm
              CONTAM 1: DBCP      78001-78365    H

    INTERV WIDTH:      500.  PERPENDICULAR:    1000.

    TRANSECT LENGTH:         4000.  AT  90. DEG

    INTERV       PERM    GRAD    THICK    LENGTH
        1       100.0   .0100    10.0     500.
        2       100.0   .0100    10.0     500.
        3       100.0   .0100    10.0     500.
        4       100.0   .0100    10.0     500.
        5       100.0   .0100    10.0     500.
        6       100.0   .0100    10.0     500.
        7       100.0   .0100    10.0     500.
        8       100.0   .0100    10.0     500.
```

The computer will search the IR Data Base for candidate subschema records.

The resultant graph will be drawn on the screen and the program will stop. If the user desires a hard copy, press [MAKE COPY]; then press [RETURN] to continue.

The computer will then ask if the same graph should be plotted on the 4662 plotter:

```
    DO YOU WANT THIS GRAPH ON THE 4662 PLOTTER?  <Y OR N>
>
```

Type "Y" and press [RETURN].

```
    LOAD 1 SHEET OF PAPER; THEN PRESS [RETURN]
>
```

The computer will pause so that the user may load a sheet of plotting paper. To continue, press [RETURN] and then the graph will be plotted.

After the plot the computer will ask if the user wishes to stop. If not, user should type "N" and answer the same questions as before.

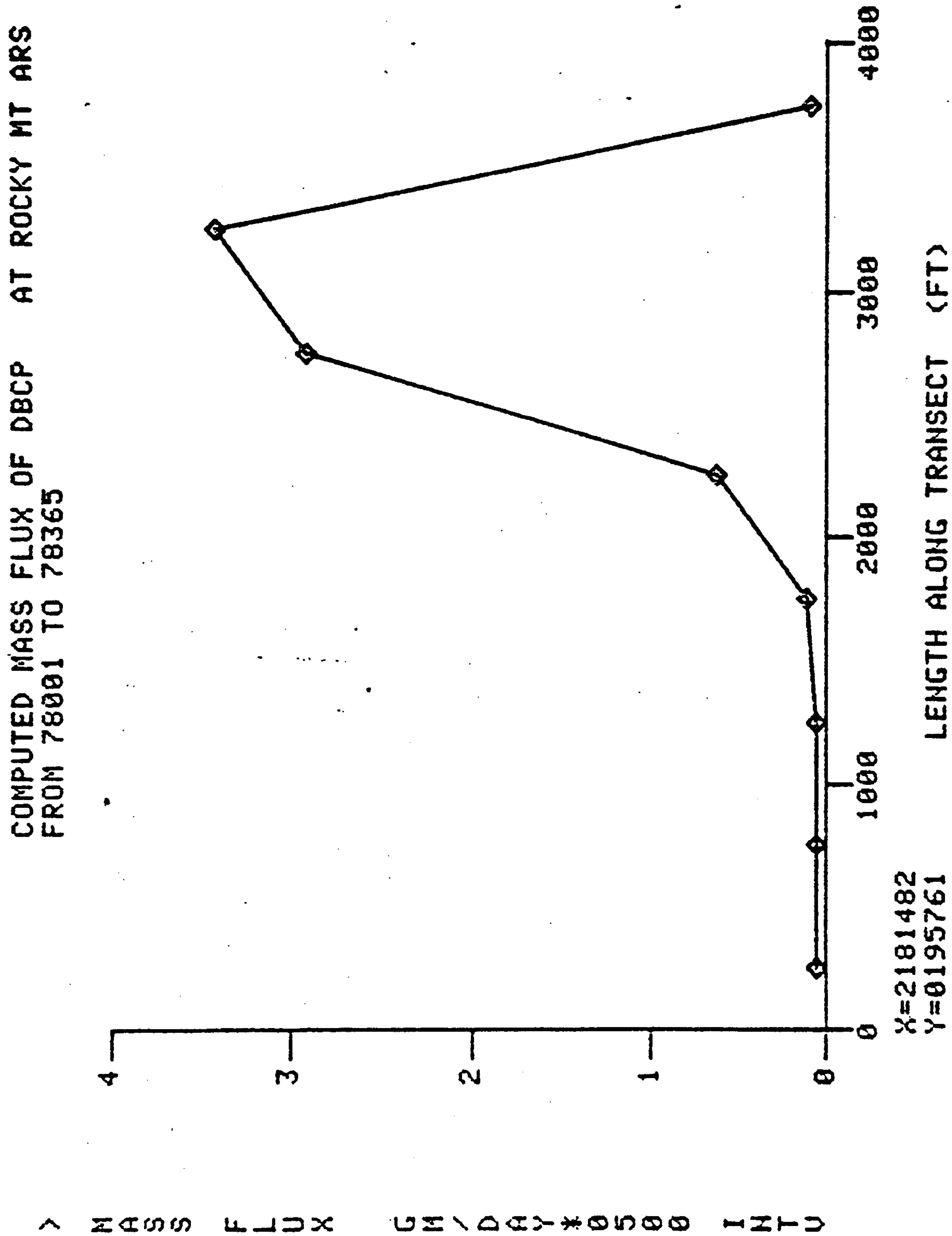
When user has completed all his computer runs, type @ADD IR*GEOLPRO.EXIT and press [RETURN] to clear the computer; the computer will respond:

```
  EXIT!
FURPUR 27R3 E33 SL73R1 05/04/79 11:18:35
END ERS.
>
```

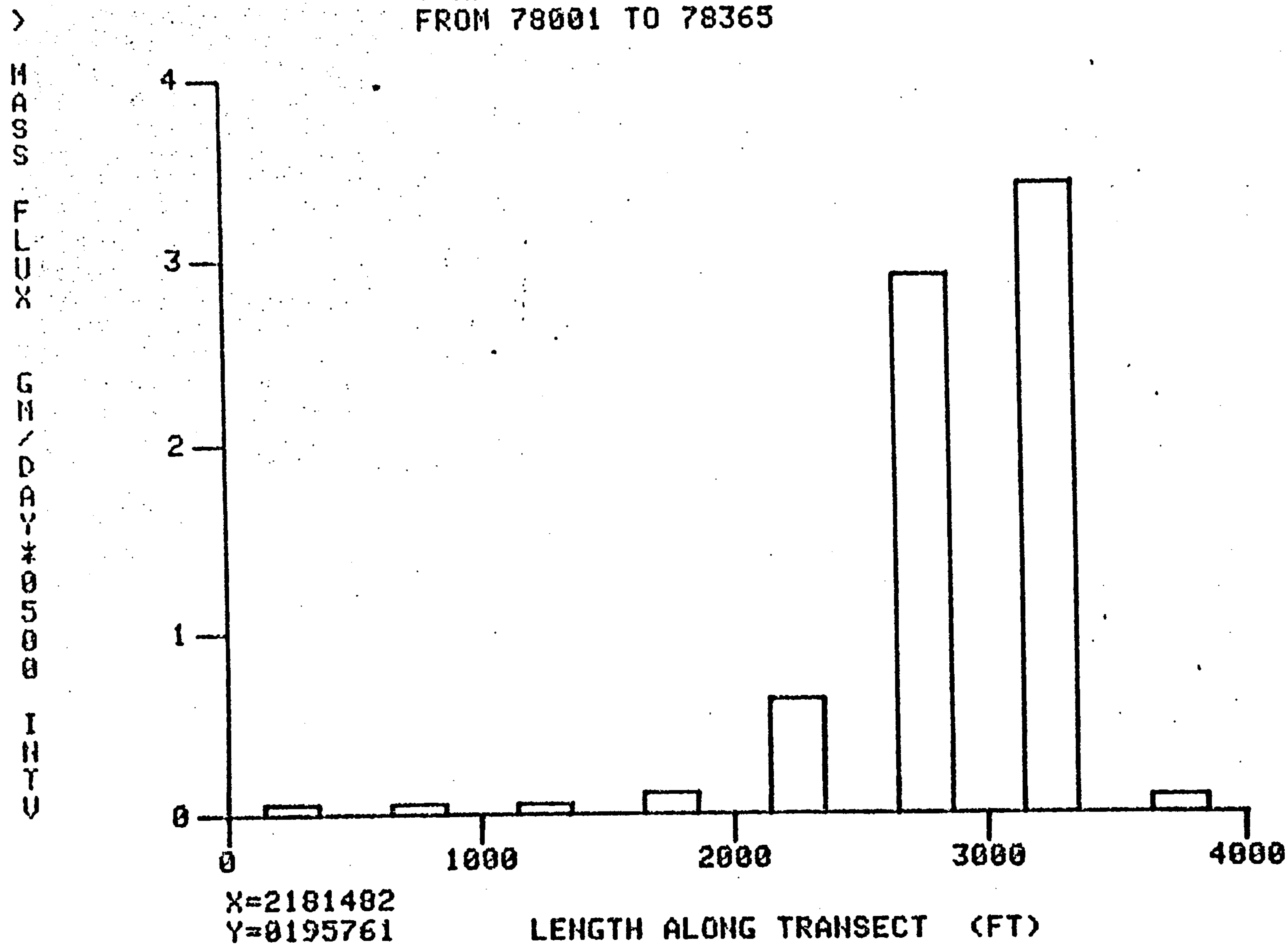
Note: If there are problems with the program, stop execution by typing @@X TIO and pressing RETURN.

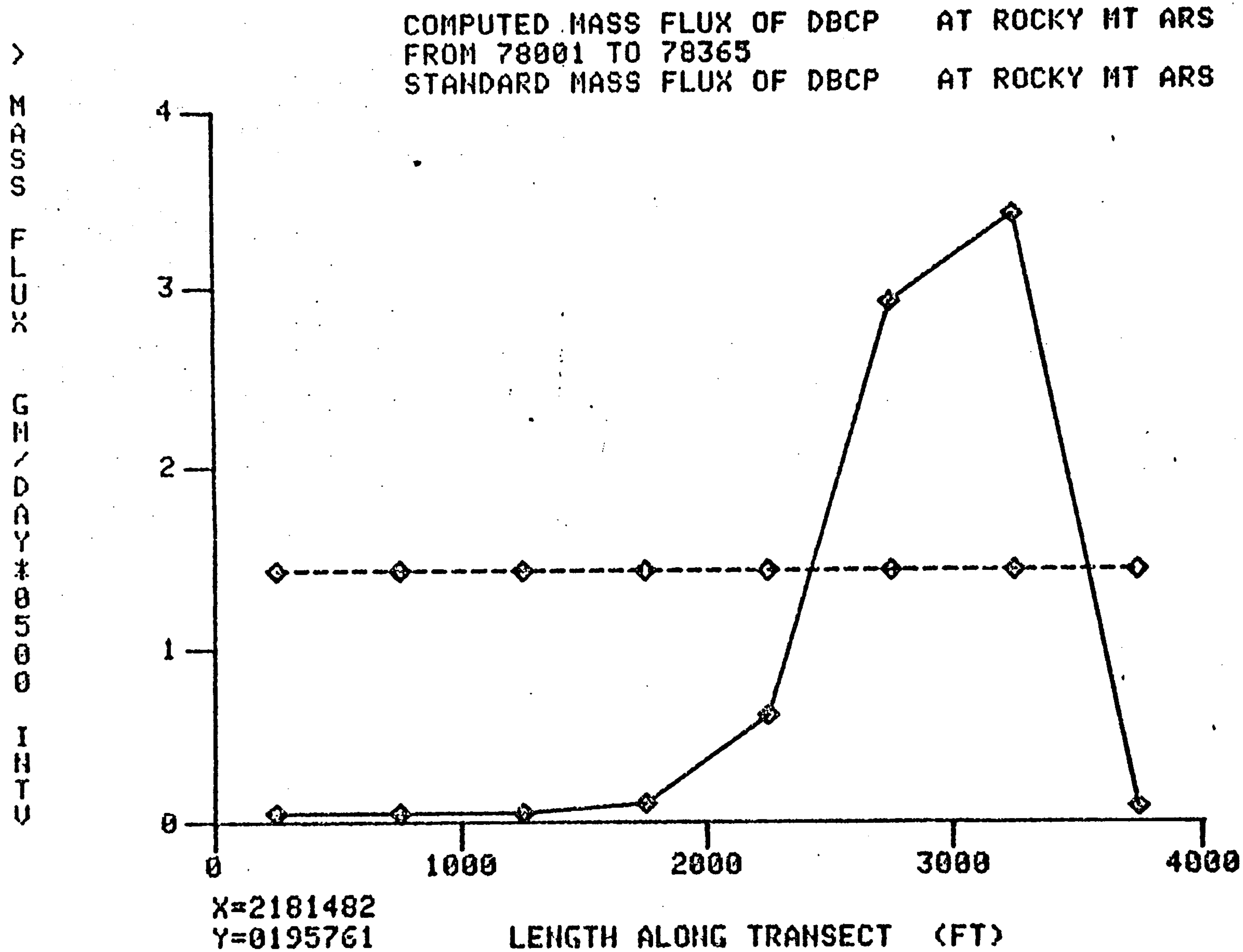
9.4.3 SAMPLE OUTPUT

Note: Computed mass flux - solid line
Standard mass flux - dashed line



COMPUTED MASS FLUX OF DBCP AT ROCKY MT ARS
FROM 78001 TO 78365




COMPUTED MASS FLUX OF DBCP AT ROCKY MT ARS
FROM 78001 TO 78365
STANDARD MASS FLUX OF DBCP AT ROCKY MT ARS
> MASS FLUX GM/DAY*0500 INTU
4
3
2
1
0
0
1000
2000
3000
4000
X=2181482
Y=0195761
LENGTH ALONG TRANSECT (FT)

Campbell/mas/2041
14 Nov 79

DRXTH-IS

SUBJECT: Proposed Position on Fluoride Treatment at RMA

Commander
Rocky Mountain Arsenal
Commerce City, CO 80022

1. Reference meeting at RMA, 4 Oct 79, between representatives of RMA, WES, and this Agency, subject as above.

2. At referenced meeting results of recently completed geohydrologic survey tasks at the north boundary of RMA and results of fluoride removal pilot tests were discussed. Because of the high costs of fluoride treatment and the uncertainty associated with the requirement to treat for fluoride upon system expansion, a decision was reached to advise the State of Colorado that the US Army does not plan to construct a fluoride removal system at this time. The ongoing design of a fluoride treatment process will be continued to allow rapid implementation if needed at a latter date.

3. Per agreements made with RMA, attached at inclosure 1 is a suggested letter for transmittal to Colorado Department of Health. Inclosure 2 is supportive data compiled by USATHAMA on the expected fluoride contaminant loading to the expanded north boundary control system.

4. Request this information be provided to the State of Colorado as soon as possible.

2 Incl
as

FRANK A. JONES, JR.
Colonel, CmlC
Commanding